

# HYDROGEN AND PREHEAT MANAGEMENT IN WELDED HIGH STRENGTH STEEL FOR DEFENSE APPLICATIONS

(TTCP Workshop and Joint Seminar)

*Volume I: Workshop Report*

## FINAL REPORT

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## **ABSTRACT**

A joint seminar and workshop on hydrogen management in high strength steel weldments were performed to assess the state of the art and science, to assess the progress of the TTCP-S11 research activities, to make mid-course corrections to the research activities and to plan for technology transfer and round-robin tests. Achievement highlights, the reorganization of activities to promote cooperative research and operation plan are described.

## **SECTION I**

### **Introduction**

## INTRODUCTION

TTCP project (S-11) on "Management of Hydrogen and Preheat in High Strength Steel Weldment for Defense Applications" has been in progress for over three years. Various activities have been completed while others are in various stages of completion. In order to thoroughly evaluate the results and transfer technical achievements to practice a joint seminar and workshop was performed which was designed to accomplish the following:

1. establish the state-of-the-science (invited speakers)
2. assess progress of the various research activities;
3. make mid-course corrections to present research activities;
4. define and implement new activities to verify or advance the objectives;
5. organize technology transfer and plan for round-robin tests;
6. establish specifications for new testing methods.

The workshop was organized into two activities. The first activity being a one day joint seminar with internationally recognized hydrogen experts who were invited to the joint seminar and workshop to present a thorough state of the art review and to enhance our understanding of material behavior. This information set the stage for the second activity of systematically assessing the progress of 23 active programs. The workshop report is given in Volume 1. The seminar papers will be published into a Proceeding book by Welding Technology Institute of Australia (WTIA) and will be soon published. These papers are also given in Volume II of this report.

The workshop program evaluated the activities grouped into three task areas. The focus of each of these tasks is given as follows:

**Task A.** Develop a family of high strength steel filler metals that can deposit crack-free weld metal without the need for preheat or postheat weld soaks.

**Task 4.** Research and develop new hydrogen cracking tests that can evaluate the susceptibility of weld metal to transverse hydrogen cracking. Combined knowledge of hydrogen cracking behavior and mechanics will be used to propose new specimen configurations and loading concepts. After testing to determine the validity of the new concepts under conditions of known hydrogen content, microstructure, and mechanical stress state, the most promising design for defense fabrication applications will be selected.

**Task 67.** Determine the relationship between hydrogen content and transverse cracking susceptibility of multiple-pass weldments. The influence of welding parameters on weld metal hydrogen content and mechanical properties will be determined. Activities under this task can be divided into methodology for shipyard weld metal hydrogen cracking prediction, arc elemental hydrogen sensors, hydrogen modeling, and relationships between welding variables and weld properties.

The two day workshop program agenda, the operating assignments as of January 1996 and the highlight for the progress made in 1996 are given in Section II. The first midcourse correction was to rearrange the activities into more consistent Tasks groups which is shown in Section III, where Task 1 is now titled "Research and Development of New Weld Hydrogen Cracking Tests", Task 2 is now titled "Determine Relationship between Welding Parameter (including hydrogen content) on Multiple Pass Weld Transverse Cracking", and Task 3 is now titled "Develop High Strength Steel Filler Metals to be used without Preheat". The milestone chart is also given in Section III. A complete description of the operating assignments, results and plans is given in Section IV, V, and VI. The man year used on this project by the various agencies is 10.7 with the distribution given in Section VII. Section VIII list the participants to the workshop and their affiliation.

## **SECTION II**

### **Operation of the Workshop**



**HYDROGEN MANAGEMENT IN HIGH STRENGTH STEEL WELDMENTS FOR DEFENCE**  
**APPLICATIONS: DAYS 2 AND 3**

Approximately 10 minutes will be allotted for each activity

**DAY 2**

0900 - 0910	Framework for the workshop	
0910 - 0940	<b>Special Guest Presentations</b> Hydrogen behaviour in welded joints: A Review of Work Performed in the E.O. Paton Electric Welding Institute	Prof. I.K. Pokhodnya
0940 - 1010	Current Ideas on Mechanisms of Hydrogen Assisted Cracking	Stan Lynch (DSTO)
1010 - 1300	<b>Task 4 Research and Development of New Weld Metal Hydrogen Cracking Tests</b> 1. Longitudinal Restraint Cracking Test 2. Modified Gapped Bead on Plate Test 3. Modified Cruciform Test 4. Measurement of $K_{ISCC}$	Session Chairman - Dr. A. Crowson Aust. - DSTO Aust. - DSTO USA - NSWCCD USA - Army Benet Lab
1100	Coffee 5. J-integral fracture toughness test procedures 6. Fatigue life in hydrogen environments 7. Martensite start temperatures as hydrogen cracking indicator 8. Multiple pass weld metal properties cooperative project 9. Inspection delay time for repair welds Task 4 "highlights", new activities and discussion of future directions	USA - Army Benet Lab USA - Army Benet Lab USA - NSWCCD Aust. - CSIRO Canada Discussion Leader: Dr. J. L. Davidson
1300 - 1400	Lunch	
1400 - 1430	<b>Special Guest Presentation</b> Finite Element Modelling of Hydrogen Induced Cracking in Multipass Welds	Dr. W. Payton (ANSTO)
1430 - 1700	<b>Task 67 Determine Relationship between Hydrogen Content and Multipass Weld Transverse Cracking</b> 1. Hydrogen -induced subcritical cracking 2. Effects of MMA welding parameters on zone toughness 3. SAW properties and heat input relationships 4. Risk evaluation of hydrogen cracking	Session Chairman - Dr. Julian Wu Aust. - DSTO Aust. - DSTO Aust. - DSTO Aust. - DSTO
1530	Coffee 5. Hydrogen transfer from welding plasma. 6. Weld pool shape and time-temperature profiles 7. Atmospheric exposure on Hydrogen pickup 8. Weld Metal Hydrogen Trapping Task 67 "highlights" and discussion of future directions	USA - NSWCCD UK - DRA USA - CSM Discussion Leader: Dave Olson

**DAY 3**

	<b>Task A Develop High Strength steel filler metals to be used without preheat</b>	Session Chairman - Dr. E. Chen
0900 - 1100	1. Review states of preheat free consumables 2. Development of ULCB wires 3. ULCB wire supplier 4. Integration of all USN efforts of filler development 5. Research Collaborations 6. Eliminate Post weld heat treatment by a electrotransport practice Task A "highlights" and discussion of future directions	Aust. - DSTO USA - NSWCCD USA - NSWCCD USA - NSWCCD USA - NSWCCD USA - CSM Discussion Leader: Brian Dixon
1100	Coffee	
1120 - 1300	Preparation of workshop report	
1300 - 1400	Lunch	
1400 - 1700	Preparation of workshop report	

**Task A.** Develop a family of high strength steel filler metals that can deposit crack-free weld metal without the need for preheat or postheat weld soaks. The effort focuses on weld metal from the ultralow carbon bainite (ULCB) system.

**Task 4.** Research and develop new hydrogen cracking tests that can evaluate the susceptibility of weld metal to transverse hydrogen cracking. Combined knowledge of hydrogen cracking behavior and mechanics will be used to propose new specimen configurations and loading concepts. After testing to determine the validity of the new concepts under conditions of known hydrogen content, microstructure, and mechanical stress state, the most promising design for defense fabrication applications will be selected.

**Task 67.** Determine the relationship between hydrogen content and transverse cracking susceptibility of multiple-pass weldments. The influence of welding parameters on weld metal hydrogen content and mechanical properties will be determined. Activities under this task can be divided into methodology for shipyard weld metal hydrogen cracking prediction, arc elemental hydrogen sensors, hydrogen modeling, and relationships between welding variables and weld properties.

**OPERATING ASSIGNMENT**  
**HYDROGEN MANAGEMENT IN HIGH STRENGTH STEEL WELDMENTS FOR DEFENSE APPLICATIONS**

Task 4 Research and Development of New Weld Metal Hydrogen Cracking Tests

Activity	Status	Results	Description	Organization
1. Longitudinal Restraint Cracking Test	completed	LRC tests found to be unconservative	The LRC Test has been applied experimentally as a multipass hydrogen cracking test and was found to be unconservative. No cracks developed in LRC tests that were conducted under conditions which were known to produce transverse hydrogen cracks in full-scale multipass welds.	Aust. - DSTO
2. Modified Gapped Bead on Plate Test	completed	Modified GBOP test was found to be unconservative	A standard Gapped Bead on Plate (GBOP) test is known to be unconservative for the determination of safe welding parameters for multipass welding. Yield strength level stresses are developed in weld metal of the GBOP test, but the hydrogen concentration of a single pass is less than that which accumulates in multiple pass welds. An attempt was therefore made to make the GBOP test conservative by immersing the test piece in ice water 30 sec. after the arc was extinguished. The aim of the quench was to decrease the rate at which hydrogen would diffuse from the test weld. Despite the "quench" treatment the test was still found to be unconservative.	Aust. - DSTO
3. Modified Cruciform Test	in progress	Modified cruciform test is being developed for the determination of hydrogen cracking	A weldability test based on a modified cruciform design was developed. The specimen contains transverse and longitudinal notches to facilitate hydrogen crack initiation. The procedure involves deposition of several layers of weld beads to develop high restraint typical of multipass welding. An interpass temperature equal to the preheat temperatures under investigation is re-established between sets of fillet weld passes. Metallographic specimen are removed after completion of welding to inspect for cracking. All weld metal tensile specimens are also removed and tested to evaluate ductility loss. The initial results of these tests are consistent with a hydrogen cracking model developed using single pass weldability tests.	USA - NSWCCD

**OPERATING ASSIGNMENT**  
**HYDROGEN MANAGEMENT IN HIGH STRENGTH STEEL WELDMENTS FOR DEFENSE APPLICATIONS**

Task 4 (continued) Research and Development of New Weld Metal Hydrogen Cracking Tests

Activity	Status	Results	Description	Organization
4. Measurement of $K_{ISCC}$	completed	new bold-load $K_{ISCC}$ ASTM test has been proposed	Measurements of $K_{ISCC}$ for A723, 13-8 steel and 718 Ni-Fe alloy in acid and electrolytic cell hydrogen environments have been made for application to liquid propellant gun combustion environments. A new bold-load $K_{ISCC}$ ASTM Test method has been proposed based on this work.	USA - Army Benet Lab
5. J-integral fracture toughness test procedures	in progress	small specimen J-Integral specimens being evaluated	J-integral fracture toughness test procedures for weld applications have been summarized with emphasis on simplified test methods suitable for small specimens cut from welds. Measurements of $J_{IC}$ fracture toughness for cleavage in as welded 4130 steel HAZ have been made for application to armament component.	USA - Army Benet Lab
6. fatigue life in hydrogen environments	in progress	test and analysis is in progress	Test and analysis of fatigue life at hydrogen environments have been described for weld applications as a way to avoid difficulties of fatigue crack growth testing of welds affected by hydrogen.	USA - Army Benet Lab
7. Martensite start temperatures as hydrogen cracking indicator	in progress	preliminary results suggest value of using $M_s$ temperatures Paper at ASM Gatlinburg Conference 95 and TMS Fall Mtg. 95.	<p>MS temperatures was shown to delineated cracking tendencies of high strength steels in hydrogen environment. The difference in MS temperatures of base metal and weld metal can indicate whether cracking will occur in the weld or HAZ.</p> <p>The successful application of MS temperatures as a cracking induce results from the large differences in hydrogen solubility and diffusion coefficient between ferrite (martensite) and austenite.</p>	USA - CSM USA - NSWCCD
8. Multiple pass weld metal properties cooperative project	in progress	AWS 96 (Chicago) fracture paper on multipass welds	A cooperative research project led by Ian French of CRSRO, has been initiated to better understand the influence of alloying additive on microstructural and mechanical properties of weld metal for shielded processes.	USA - CSM Aust. - CISRO

# **OPERATING ASSIGNMENT** **HYDROGEN MANAGEMENT IN HIGH STRENGTH STEEL WELDMENTS FOR DEFENSE APPLICATIONS**

Task A Develop High Strength steel filler metals to be used without preheat.

Activity	Status	Results	Description	Organization
1. Review states of preheat free consumables	completed	Established a knowledge base and found source for experimental wires	Review present states of "preheat free" consumables and discuss test matrix with potential suppliers of experimental matrix.	Aust. - DSTO
2. Development of ULCB wires	in progress	Influence of nickel addition to weld deposit reported	Development of ULCB wires has shown that increasing the Ni content had a beneficial effect on impact toughness. Also decreasing inclusion volume fraction increased upper shelf energy and decreases 50% FATT.	USA - NSWCCD
3. ULCB wire supplier	completed	memorandum of understanding signed	A memorandum of understanding was signed with Hobart to develop 100 ksi yield metal-cored ULCB wires.	USA - NSWCCD
4. Integration of all USN efforts of filler development	completed	integrated plan is in place and working	A comprehensive program plan was put forth to integrate all U.S. Navy-funded efforts to develop filler metals that do no require preheat or post heat soaking.	USA - NSWCCD
5. Research Collaborations	initiated	potential acceleration of filler development and qualifications	Extensive collaborations were initiated with various program participants to design a matrix of solid, flux-cored, and metal covered wires. NSWCCD is performing weldability testing. Electric Boat division and Nat. Center for Excellence in Metalworking Tech. and Oregon Graduate Inst. are evaluating mechanical properties.	USA - NSWCCD USA - Electric Boat USA - NCENT USA - QGI
6. Eliminate Post weld heat treatment by a electrotransport practice	completed	theoretically possible for small parts	The concept of using electrotransport to reduce diffusible hydrogen levels was evaluated using transport calculations. The application of electrotransport during the welding thermal cycle maybe useful in reducing hydrogen cracking susceptibility in small technical assemblies that might otherwise experience distortion or unacceptable microstructural changes as a result of conventional post weld soak.	USA - CSM

**OPERATING ASSIGNMENT**  
**HYDROGEN MANAGEMENT IN HIGH STRENGTH STEEL WELDMENTS FOR DEFENSE APPLICATIONS**

Task 67 Determine Relationship between Weld Parameters, Hydrogen Content and Multipass Weld Transverse Cracking

Activity	Status	Results	Description	Organization
1. Hydrogen -induced subcritical cracking	in progress	Technique has been developed to determine relationships for ultrahigh strength steels	An experimental technique has been developed which promises to deliver fundamental information regarding the relationship between the hydrogen-induced sub-critical crack growth rate and both microstructures and diffusible hydrogen content. Presently working on deposits from E120S filler metal.	Aust. - DSTO
2. Effects of MMA welding parameters on zone toughness	completed	comprehensive investigation has been completed and published	A comprehensive investigation on the effects of MMA welding parameters on zone toughness has been achieved. Greatest weld toughness occurred at high interpass temperatures (160C) and low heat inputs (1.2 kJ/mm). For HAZ regions, levels of toughness were similar when using high preheat/low input and low preheat/high heat input techniques.	Aust. - DSTO
3. SAW properties and heat input relationships	completed	Equations were developed for prediction of weld metal hardness from process parameters	For bead-on-plate submerged arc welds, the rate of variation in HAZ hardness with increased heat input and interpass temperature was quantified.	Aust. - DSTO
4. Risk evaluation of hydrogen cracking	completed	No significant evidence of cracking	An experimental submarine section, which was welded using wide range of welding procedures, was evaluated as to the risk of hydrogen cracking and embrittlement.	Aust. - DSTO
5. Hydrogen transfer from welding plasma.	in progress	Model is being developed to allow prediction of weld metal hydrogen content	Hydrogen distribution and migration from the welding plasma to the solidified weld metal is being modeled. The model is being developed for GMA welding and will incorporate feed metal and resulting papilla characteristic of GMAW. The model utilized spectrographic data supplied by the hydrogen sensor to establish the initial hydrogen species in the plasma.	USA - NSWCCD

**OPERATING ASSIGNMENT**  
**HYDROGEN MANAGEMENT IN HIGH STRENGTH STEEL WELDMENTS FOR DEFENSE APPLICATIONS**

Task 67 (continued) Determine Relationship between Weld Parameters, Hydrogen Content and Multipass Weld Transverse Cracking

Activity	Status	Results	Description	Organization
6. Weld pool shape and time-temperature profiles	in progress	Information necessary for weld metal microstructures and toughness prediction	The arc sensing model (described above in #5) will be extended to determine weld pool shape and time-temperature profiles associated with GMA welding. Currently, relationships between weld metal microstructures and toughness are being established.	USA - NSWCCD
7. Atmospheric exposure on Hydrogen pickup	completed	weld metal properties were unaffected by storage of vacuum packaged MMA electrodes	The effect of atmospheric exposure on the hydrogen pick-up of vacuum packaged Q1 (N) MMA consumables has been evaluated. Electrodes experienced very little hydrogen pick up and weld metal properties were unaffected.	UK - DRA
8. Weld Metal Hydrogen Trapping	in progress	Manuscript nearly finished	A literature review of hydrogen trapping is in preparation. Experimental work to evaluate effective gettering on trapping alloy additions is in progress.	USA - CSM

# TTCP OPERATING ASSIGNMENT PTP1 - 013

## Progress and Highlights

- **Hydrogen Cracking Tests**

Hydrogen cracking tests are being evaluated for their ability to relate cracking tendency to welding practice, weld configuration and associated materials. Efforts have been particularly focussed on transverse weld metal cracking. Some of this work has resulted in the modification of an ASTM Testing Specification. A new initiative will address criteria for the testing of weld repair procedures: the worst case scenario.

- **Austenite Decomposition Temperature**

A new concept using the austenite decomposition temperature as an indice for predicting diffusible hydrogen content and distribution is being developed. Comparison of the austenite decomposition between the weld deposit and the base material has been shown to predict whether the hydrogen distribution will promote cracking in the weld metal or in the heat affected zone. This indice will be of value in the selection of the proper welding consumable for a given high strength steel.

- **Hydrogen Arc Sensor**

A hydrogen arc sensor has been developed which is able to determine the hydrogen content in the arc. These hydrogen arc signals have been directly related to the weld metal hydrogen content. This in process hydrogen analysis will greatly improve quality assurance and gives an indication of improper hydrogen conditions while the welding is being performed. It is anticipated that with further development involving evaluation of the resiliency of this analytical practice to variation in the welding parameters and some round robin testing, this sensor will be ready for introduction to the fabrication operation involving automatic welding of high strength steels.

- **Arc Plasma Chemistry for Low Hydrogen Uptake**

The introduction of small amounts of fluorine into the welding plasma under controlled oxygen contents has been shown through both theoretical and experimental investigations to reduce the diffusible hydrogen content in high strength steel weld deposits. The fluorine is introduced as controlled amounts of specific fluorides in the welding consumable. Implementation of this approach of hydrogen management will require further research and the close cooperation with the welding consumable manufacturers.

- **Hydrogen Trapping**

The concept of using specific hydrogen traps in weld metal has been shown theoretically to be a promising method of reducing and controlling diffusible hydrogen in high strength weldments. The shared knowledge of the diffusible and residual hydrogen contents, obtained by the various TTCP members has given preliminary indications that this concept will work if properly applied. Experimental work involving specially prepared welding consumables is in progress and will evaluate our ability to put this concept into practice.



## **SECTION III**

### **Reorganization of the Operating Assignment Tasks**

## TASK 1

### RESEARCH AND DEVELOPMENT OF NEW WELD HYDROGEN CRACKING TESTS

1. Longitudinal Restraint Cracking Test  
Australia-DSTO
2. Modified Gapped Bead on Plate Test  
Australia-DSTO
3. Modified WIC Test  
USA-NSWCCD
4. Measurement of K<sub>IEAC</sub>  
USA-Army Benet Lab.
5. J-integral Fracture Toughness Test Procedures  
USA-Army Benet Lab.
6. Fatigue Life in Hydrogen Environments  
USA- Army Benet Lab.
7. To Survey Worst Case Scenario for Hydrogen Cracking in  
Fabrication  
Australia-DSTO  
Australia-ASC  
USA-NSWCCD
8. Develop Testing Criterion for Weld Repair  
Australia-DSTO  
Australia-ASC
9. Modelling of Electronic Bonding of Hydrogen in the Zone  
Ahead of Sub-critical Cracks in Ferrous Alloys  
USA-Army ARL  
USA-CSM

## TASK 2

DETERMINE RELATIONSHIP BETWEEN WELDING PARAMETERS (INCLUDING HYDROGEN CONTENT) ON MULTIPLE PASS WELD TRANSVERSE CRACKING

1. Hydrogen Induced Subcritical Cracking  
Australia-DSTO
2. Hydrogen Cracking and Heat Input  
Australia-DSTO
3. Risk Evaluation of Hydrogen Cracking  
Australia-DSTO
4. Hydrogen Arc Sensing and Modelling to Predict Weld Metal Hydrogen Content  
USA-NSWCCD
5. Modelling of Hydrogen Cracking Behavior in a Repair Weld  
Canada-DREA
6. Eliminate Post Weld Heat Treatment by a Electrotransport Practice  
USA-CSM
7. Characterisation of Undermatched Weldments  
USA-NSWCCD

### TASK 3

#### DEVELOP HIGH STRENGTH STEEL FILLER METALS TO BE USED WITHOUT PREHEAT

1. Preheat Free MMA and FCA Welding Consumables  
Australia-DSTO
2. Development of ULCB Wires  
USA-NSWCCD
3. ULCB Wire Evaluation  
USA-NSWCCD
4. Evaluation of ULCB MCAW Consumables  
USA-NSWCCD
5. Fluoride Additions to Control Weld Hydrogen Content  
USA-CSM
6. Austenite Decomposition Temperature as Hydrogen Cracking Indicator  
USA-CSM  
USA-NSWCCD
7. Multiple Pass Weld Metal Properties Cooperative Project  
  
Australia-CISRO  
USA-CSM
8. Reduction of Diffusible Hydrogen Through The Use of Weld Metal Traps  
USA-CSM
9. Analytical Methods to Evaluate Weld Hydrogen Distribution  
USA-CSM  
USA-SUNY Albany



## **SECTION IV**

### **TASK 1**

#### **Research and Development of New Weld Hydrogen Cracking Tests**

TASK 1 .

RESEARCH AND DEVELOPMENT OF NEW WELD HYDROGEN CRACKING TESTS

1. Longitudinal Restraint Cracking Test  
Australia-DSTO
2. Modified Gapped Bead on Plate Test  
Australia-DSTO
3. Modified WIC Test  
USA-NSWCCD
4. Measurement of K<sub>IEAC</sub>  
USA-Army Benet Lab.-ARDEC
5. J-integral Fracture Toughness Test Procedures  
USA-Army Benet Lab.-ARDEC
6. Fatigue Life in Hydrogen Environments  
USA- Army Benet Lab.-ARDEC  
UK-Univ. of Cranfield
7. To Survey Worst Case Scenario for Hydrogen Cracking in  
Fabrication  
Australia-DSTO  
Australia-ASC  
USA-NSWCCD
8. Develop Testing Criterion for Weld Repair  
Australia-DSTO  
Australia-ASC
9. Modeling of Electromagnetic Bonding of Hydrogen in the Zone  
Ahead of Sub-critical Cracks in Ferrous Alloys  
USA-Army ARL  
USA-CSM  
Australia-DSTO

OPERATING ASSIGNMENT PTP1 - 013 (October 25, 1996)

HYDROGEN MANAGEMENT IN HIGH STRENGTH STEEL WELDMENTS FOR DEFENCE APPLICATIONS

Task 1 Research and Development of New Weld Metal Hydrogen Cracking Tests

Activity	Status	Results	Description	Organisation
1. Longitudinal Restraint Cracking Test	in progress	LRC tests found to be unconservative	The longitudinal restraint cracking (LRC) test has been trialed as a multipass hydrogen cracking test and was found to be unconservative. LRC test were conducted under conditions which were known to produce transverse hydrogen cracks in full scale multipass welds, yet no cracks were developed in the tests. Future work will include increasing the length of the weld to increase the longitudinal residual stress.	Aust. - DSTO
2. Modified Gapped Bead on Plate Test	completed	Modified GBOP test was found to be unconservative	The standard Gapped Bead on Plate (GBOP) test is known to be unconservative for determining safe welding parameters for multipass welding. Yield strength level stresses are developed in the weld metal of the GBOP test, however, the hydrogen concentration of a single pass is less than that which accumulates in multipass welds. An attempt was therefore made to make the GBOP test conservative by immersing the test piece in ice water 30s after the welding arc was extinguished. The aim of the "quench" was to decrease the rate at which hydrogen could diffuse from the test weld. Despite the "quench" treatment the test was still found to be unconservative.	Aust. - DSTO
3. Modified WIC Test	in progress	Modified cruciform test is being developed for the determination of hydrogen cracking	Design of a modified WIC test to rapidly assess highly weldable material.	USA - NSWCCD



Task 1 (continued) Research and Development of New Weld Metal Hydrogen Cracking Tests

Activity	Status	Results	Description	Organisation
4. Measurement of $K_{IEAC}$	in progress	new bolt-load $K_{IEAC}$ ASTM test has been accepted	A large effect of yield stress on the $K_{IEAC}$ on A723 steel has been observed. $K_{IEAC}$ tests on A723 steels at yield strength levels between 1130 and 1275MPa are being performed. $K_{IEAC}$ tests are also being investigated on isothermally processed A723 steel.	USA - Army Benet Lab
5. J-integral fracture toughness test procedures	in progress	small specimen J-Integral bend test has been evaluated	Dynamic $J_{IC}$ tests will be conducted on A723 steel as part of ASTM round robin study.	USA - Army Benet Lab
6. Fatigue life in hydrogen environments	in progress	fatigue life test and analysis methods are being studied	A new analysis has been described for characterising fatigue life, including local stresses and initial crack. This work is being conducted jointly with U.Parker (Univ. of Cranfield, UK) "Fatigue Intensity Factor" concept shows significant effect of hydrogen environment on fatigue life of high strength steel armament structures 9 <sup>th</sup> International Conference on Fracture April 1997.	USA - Army Benet Lab
7. To survey worst case scenario for hydrogen cracking in fabrication	Initiating	group consensus of need	As a basis for determining the most appropriate test procedure, seek descriptions of worst case scenarios for hydrogen cracking in fabrication. The descriptions are to be circulated for comment.	Aust. - DSTO Aust. - ASC USA - NSWCCD
8. Develop testing criterion for weld repair	initiated	group consensus for need	The progressive aging of existing Naval platforms has necessitated the development of hydrogen cracking tests for weld repair. This condition potentially represents a worst case scenario for hydrogen cracking susceptibility.	Aust. - DSTO Aust. - ASC
9. Modelling of Electronic bonding of hydrogen in the zone ahead of sub-critical cracks in ferrous alloys	initiated	application of new modelling approaches	Determine relative energies of interstitials to migrate into this zone. Characterise the intraplanar bonds when interstitials are present (eg. Establish if these interstitials change the nature of these bonds by promoting/hindering crack tip propagation in this zone)	US Army - ARL

## Task 1: Hydrogen Cracking Tests

### Activity 1: The Longitudinal Restraint Cracking Test

Australia-DSTO

The Longitudinal Restraint Cracking Test (LRC) has been applied experimentally as a multipass hydrogen cracking test.

Results: The LRC test was found to be unconservative. No cracks developed in LRC tests that were conducted under conditions which were known to produce transverse hydrogen cracks in full-scale multipass welds.

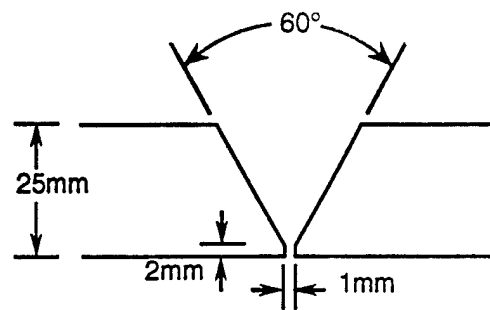
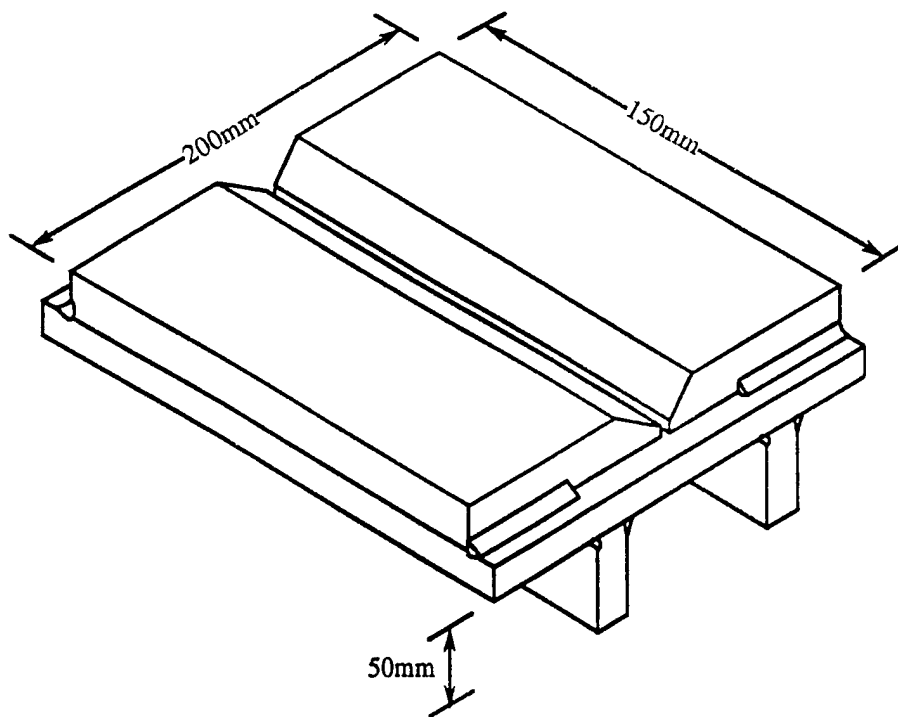
Plans: Future work will include increasing the length of the weld to increase the longitudinal residual stress.

Status: in progress

Completion: 1996, Q4

previously

Task 4  
Activity 1



## Longitudinal restraint cracking test

**DSTO**   
**AUSTRALIA**

## Task 1: Hydrogen Cracking Tests

### Activity 2: Modified Gapped Bead on Plate Test

Australia-DSTO

The standard Gapped Bead on Plate (GBOP) test is known to be unconservative for determining safe welding parameters for multipass welding. Yield strength level stresses are developed in the weld metal of the GBOP test specimen, however, the hydrogen concentration of a single pass is less than that which accumulates in multipass welds. An attempt was therefore made to make the GBOP test conservative by immersing the test piece in ice water 30s after the welding was extinguished. The aim of the "quench" was to decrease the rate at which hydrogen could diffuse from the test weld.

During laboratory scale preheat free welding tests only the first pass is preheat free. Thereafter the temperature of the small test piece is elevated by the previous pass or passes. Subsequent passes may then be deposited soon after the first, at an elevated interpass temperature or after the piece has cooled to some low pre-defined temperature. If time is allowed for the test piece to cool then hydrogen from earlier passes will have time to diffuse from the weld and the effects of hydrogen buildup will be reduced. If a pass is deposited soon after the previous pass then the previous pass will have effectively preheated the test piece and the test is not really a test of preheat free welding. While preheating by earlier passes will also occur in a full scale structure, the effect will be reduced by the greater heat sink offered by the surrounding parent metal.

Results: Despite the "quench" treatment the test was still found to be unconservative.

Status: completed

previously

Task 4  
Activity 2

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## Hydrogen Induced Cracking of a Flux Cored Arc Weld Metal - GBOP Test

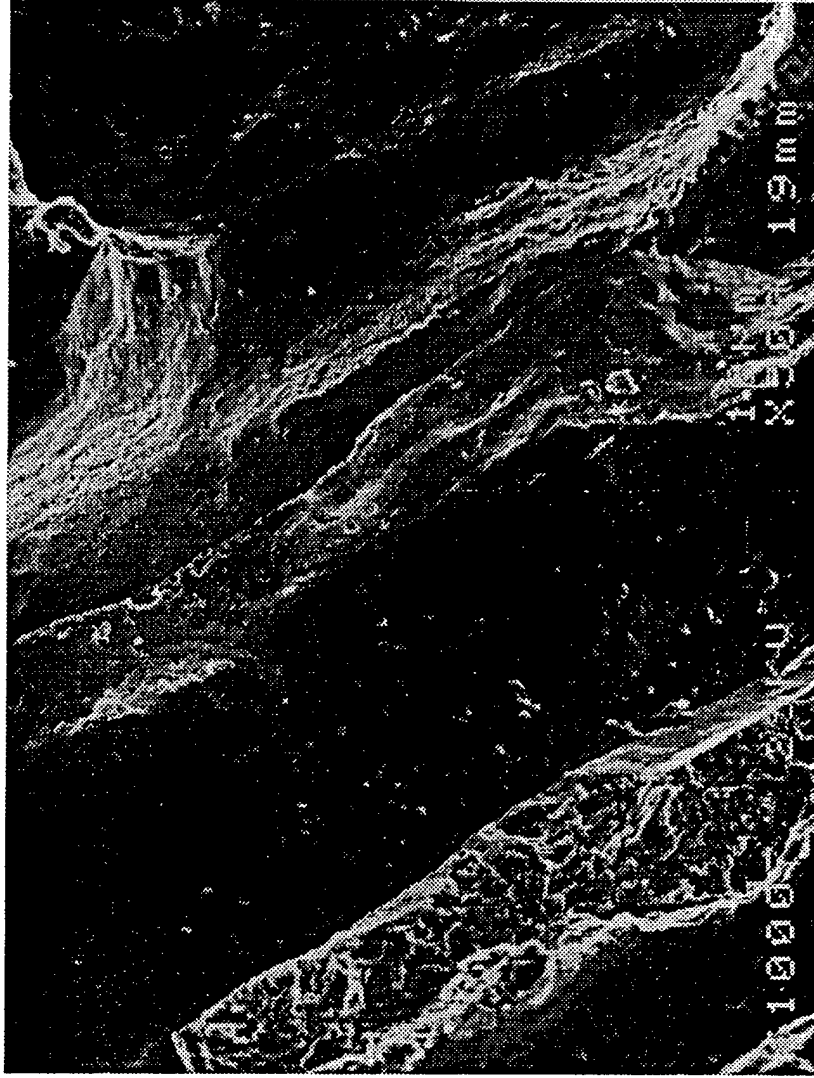


Ship Structures and Materials Division

DSTO

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## Hydrogen Induced Cracking of a Flux Cored Arc Weld Metal - Multipass Weld



Ship Structures and Materials Division

DSTO

## Task 1: Hydrogen Cracking Tests

### Activity 3: Modified Cruciform Test

USA-NSWCCD

Design of a modified WIC test to rapidly assess highly weldable new materials for cracking, including hydrogen cracking. The modified cruciform test has been found successful in detecting the propensity for transverse cracking in multipass welds and weld metal embrittlement (via loss of ductility in all weld metal tensile specimen). Research on the development of new hydrogen cracking test by designing a modified WIC type of test is in progress. The major differences between present practice and the modified approach being investigated is that the modified approach will use thicker plate and modified joint design to increase the thermal severity of the test. A test fixture will be developed to restrain the specimen during the test. Previously the specimen was welded to the plate. This practice required additional work to remove and inspect the specimen.

The modified specimens are being designed to evaluate both the longitudinal and transverse cracking. The specimen contains transverse and longitudinal notches to facilitate hydrogen crack initiation. The procedure involves deposition of several layers of weld beads to develop high restraint typical of multipass welding. An interpass temperature equal to the preheat temperature under investigation is being used between sets of fillet weld passes. Metallographic specimen are removed after completion of welding to inspect for cracking. All weld metal tensile specimens are also removed and tested to evaluate ductility loss.

Results: The initial results of these tests are consistent with a hydrogen cracking model developed using single pass weldability tests.

Plans: A document describing the modified cruciform test procedures using AWS B.4 format will be prepared.

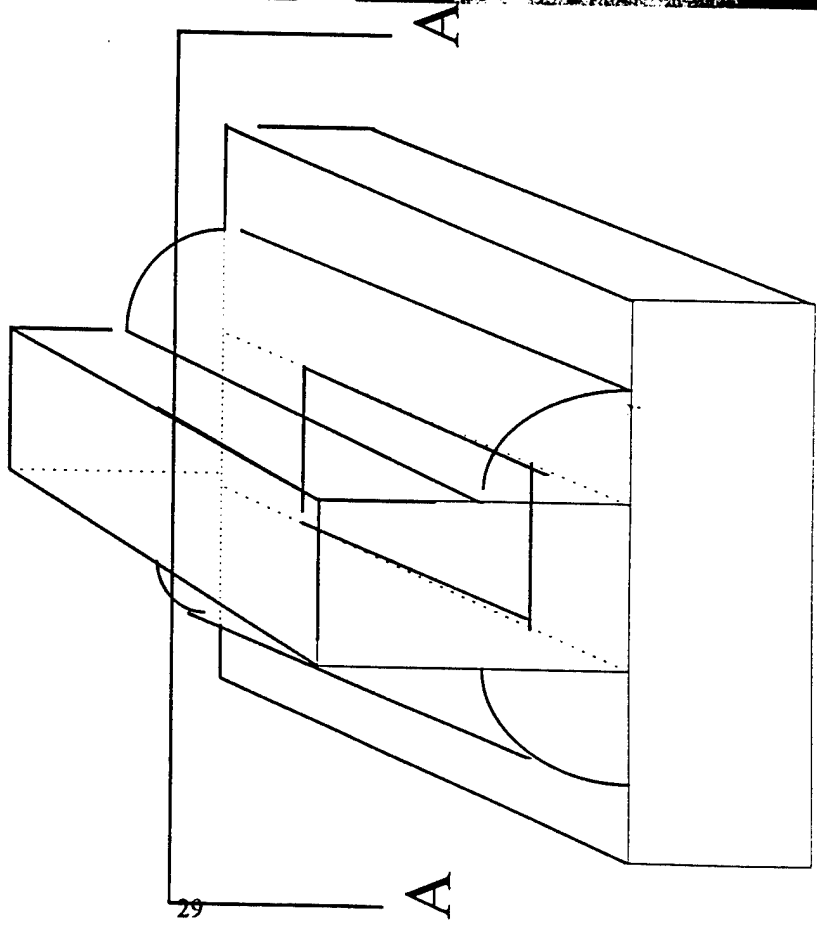
Status: in progress

Completion: 1997, Q2

Previously

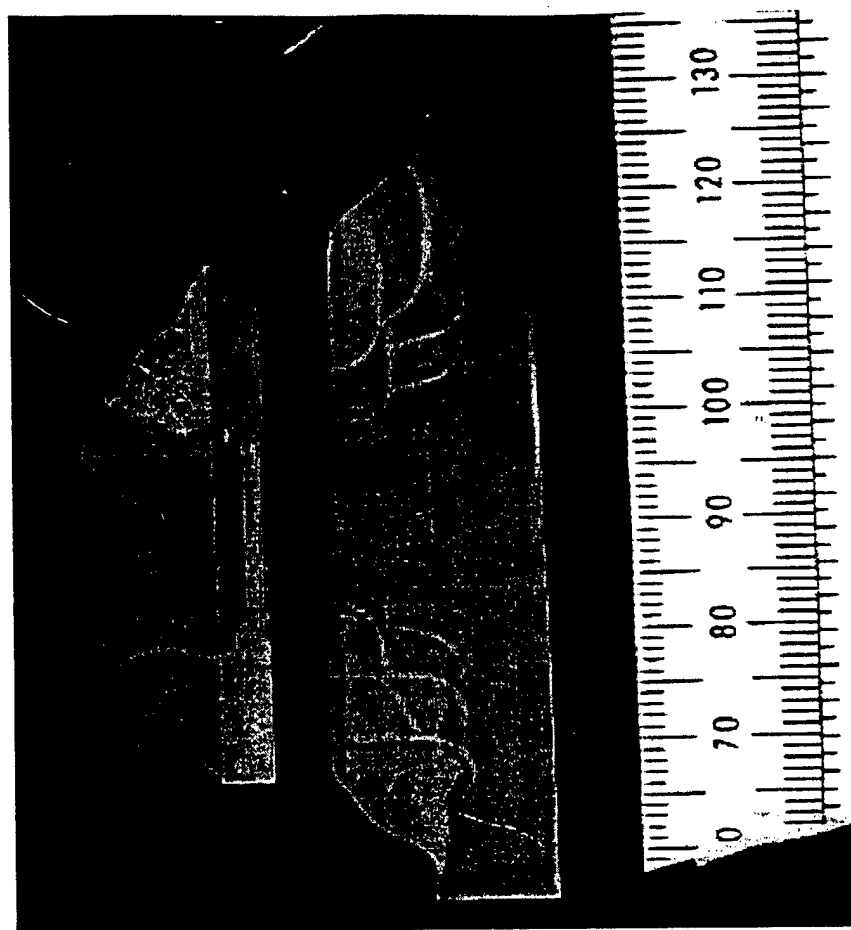
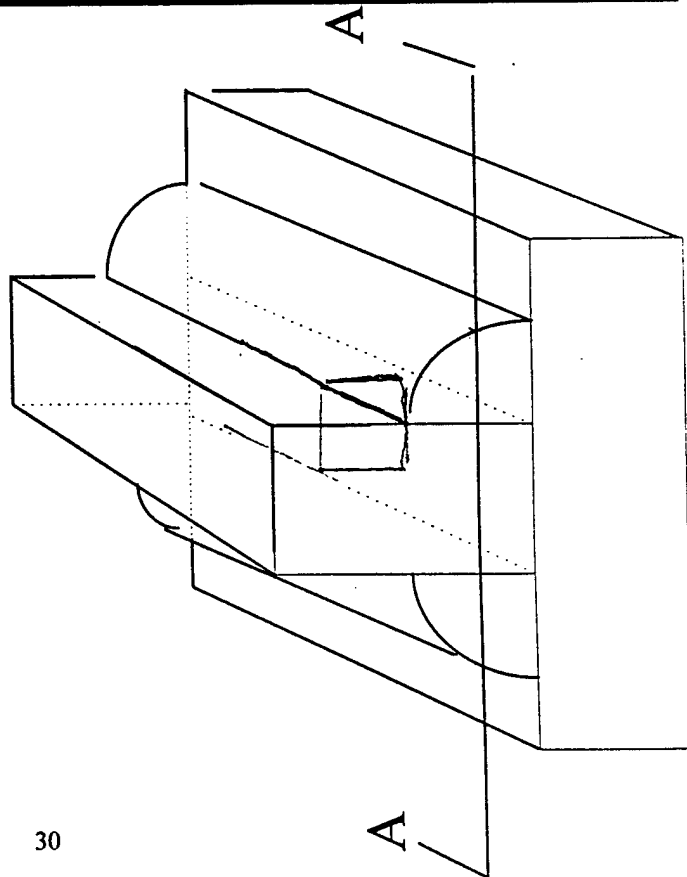
Task 4  
Activity 3

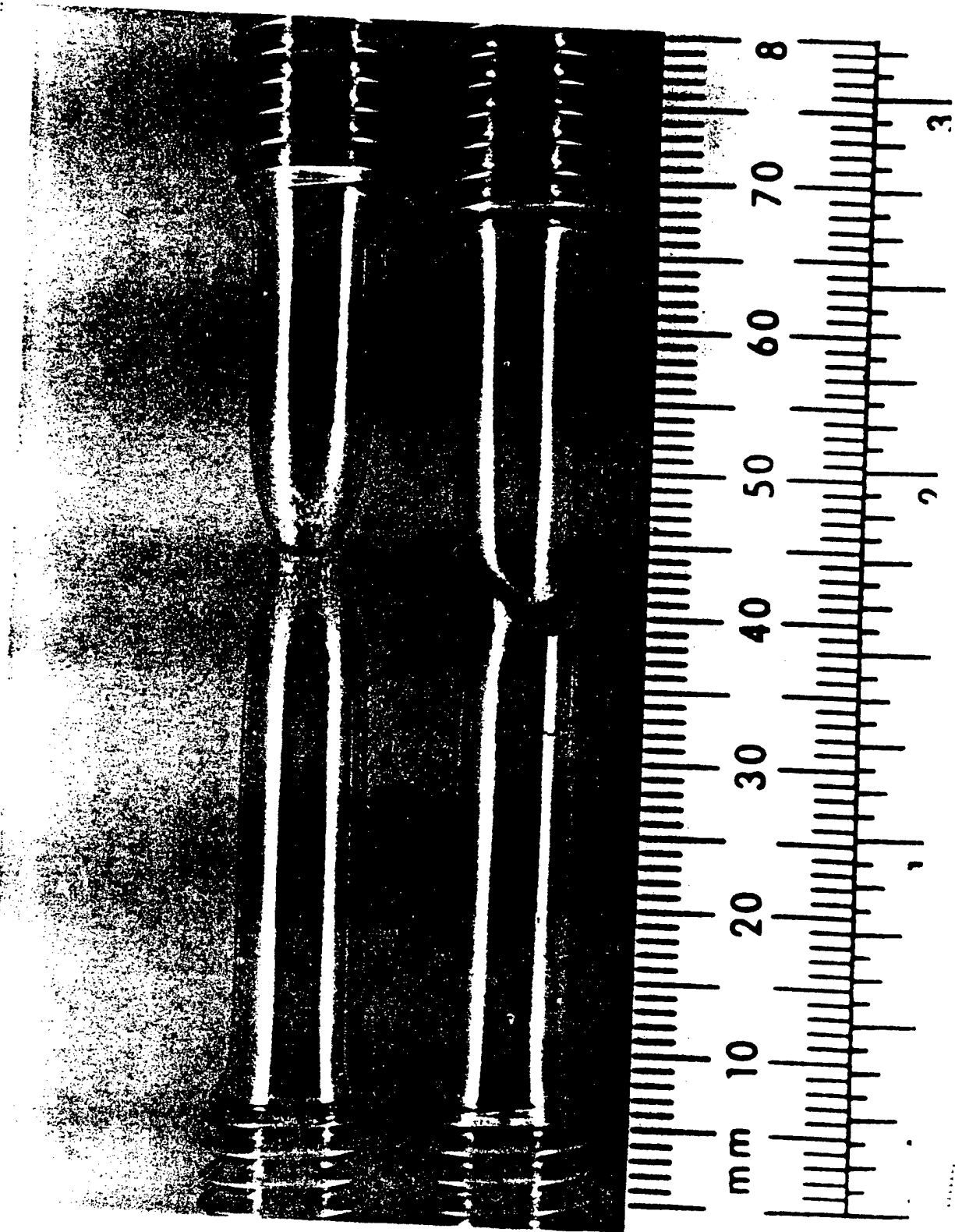
# Longitudinal Notch



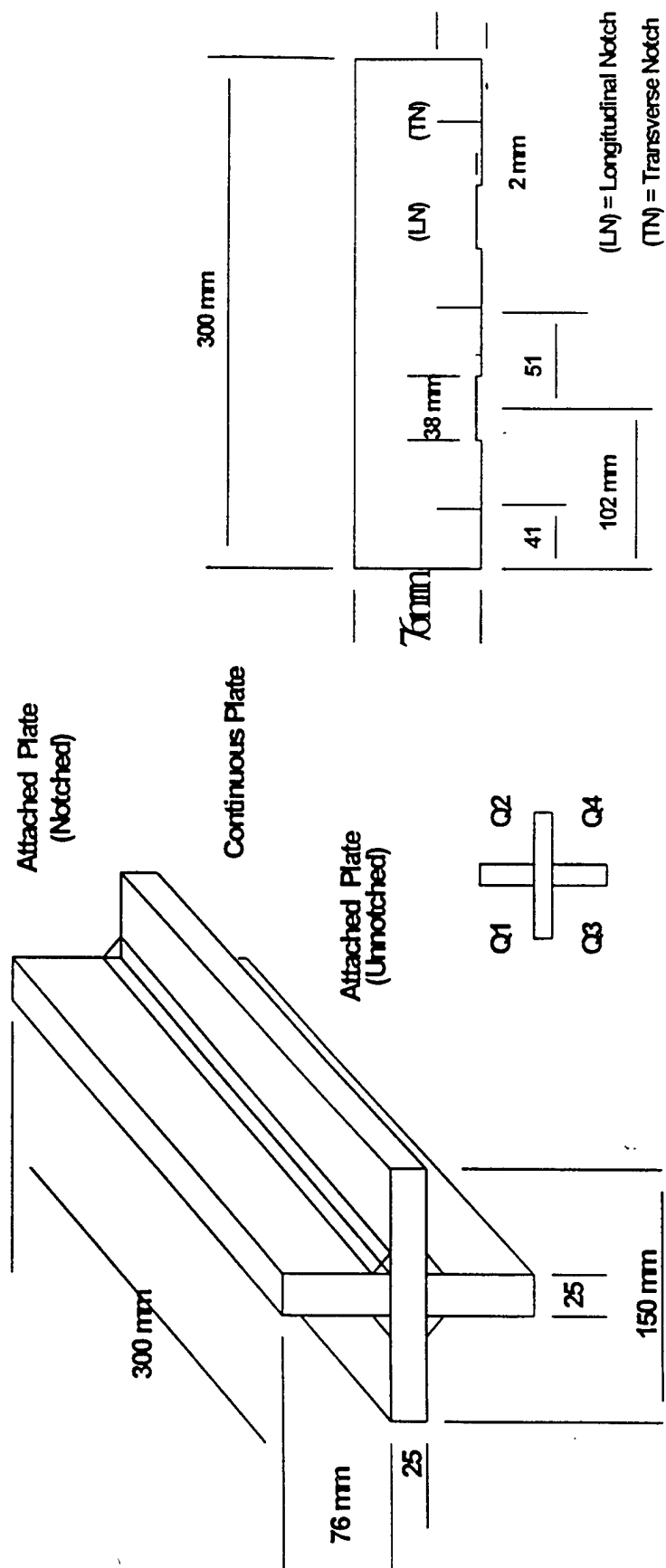


# Transverse Notch



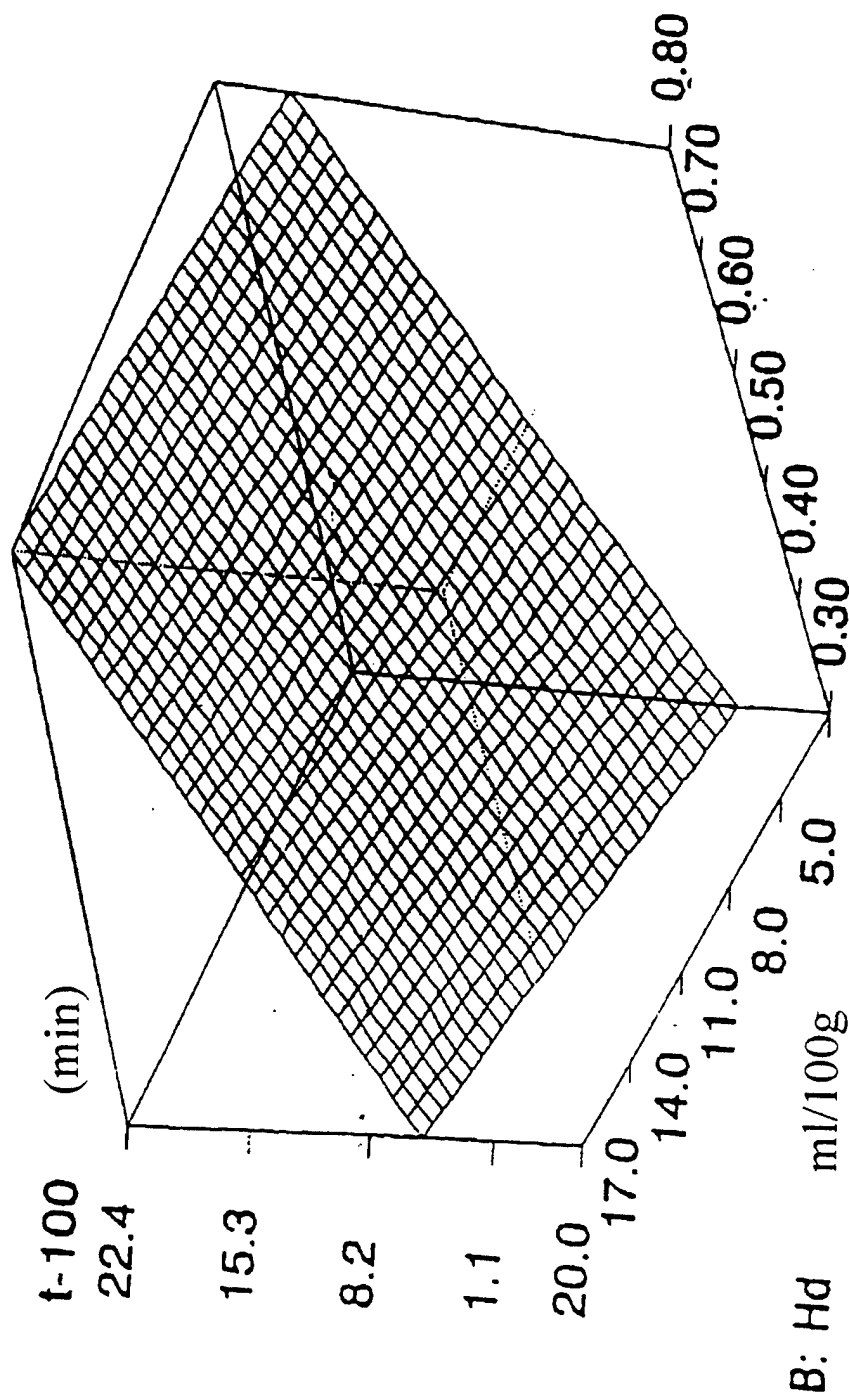


# Modified Cruciform Specimen



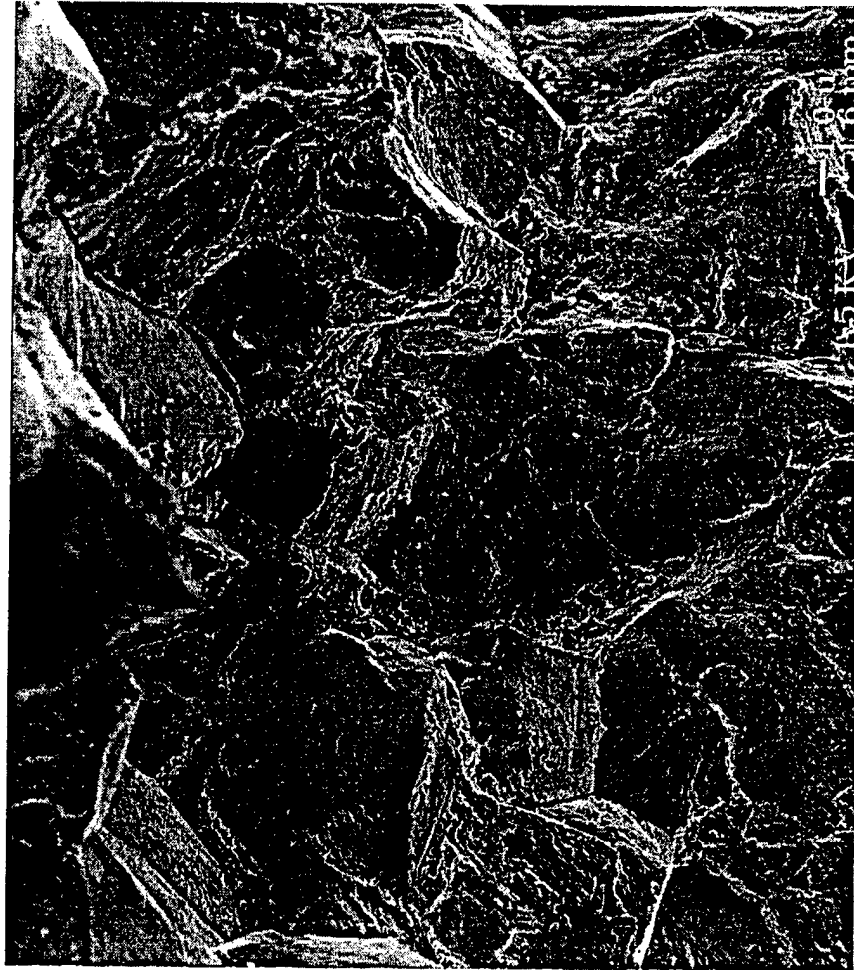
# Hydrogen Cracking Response Surface

$$t_{100, \min} = 34.1(\text{CEN}) + (\text{Hd}-5)/3.5 - 9.1$$



23 Oct

# Fracture Surface of Hydrogen Crack (Weld Metal)



Task 1: Hydrogen Cracking Tests

Activity 4: Measurement of Kieac for Higher Strength Steels

USA-Army Benet Laboratory-ARDEC

Kieac tests on A723 steels at yield strength levels between 1130 and 1275 MPa are being performed. Kieac tests are also being used to investigate isothermally processed A723 steel.

Results: A large effect of yield stress on the Kieac for A723 steel has been observed.

Plans: work in progress

Status: in progress

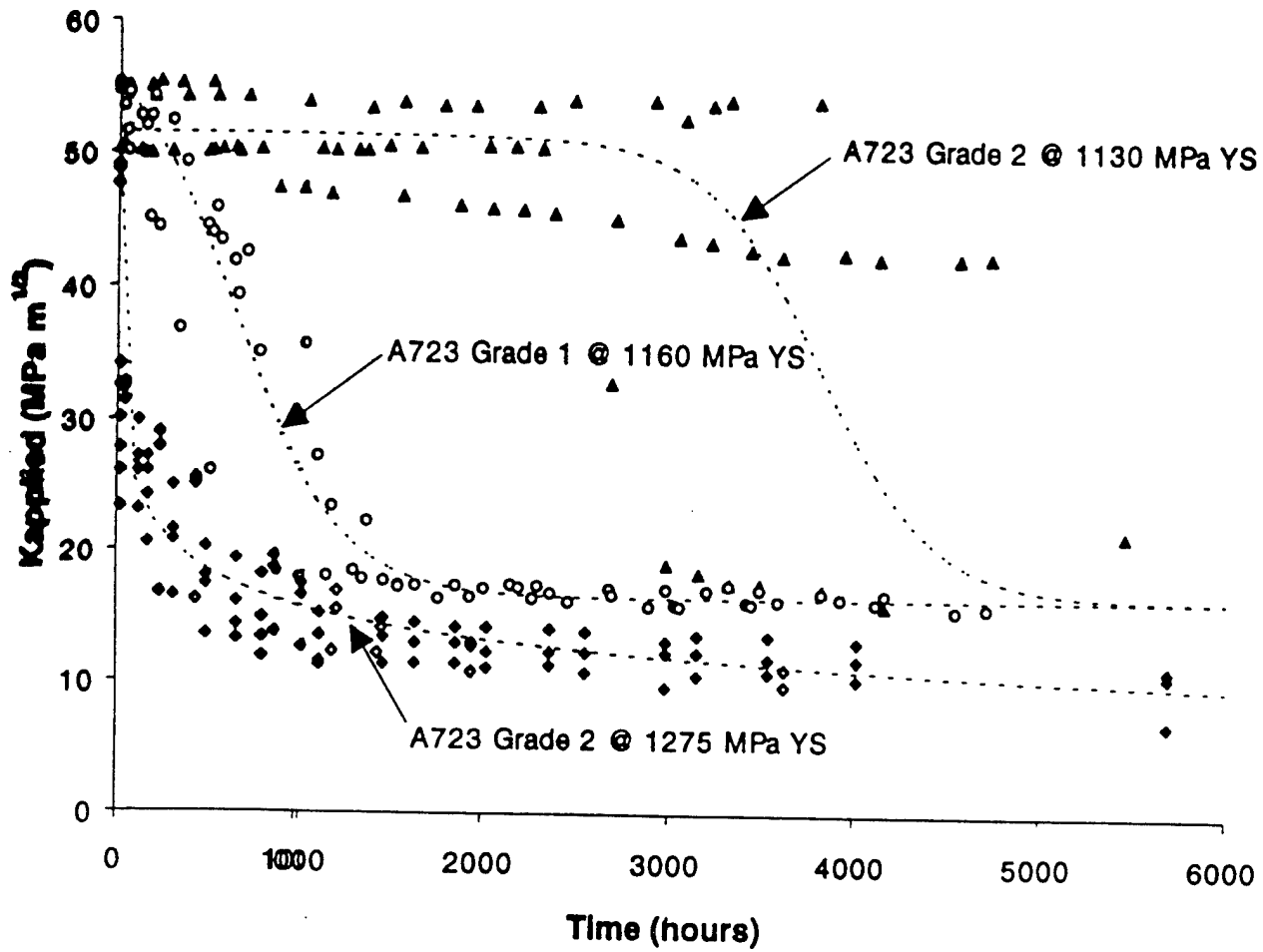
Completion: 1997, Q3

Previously

Task 4  
Activity 4

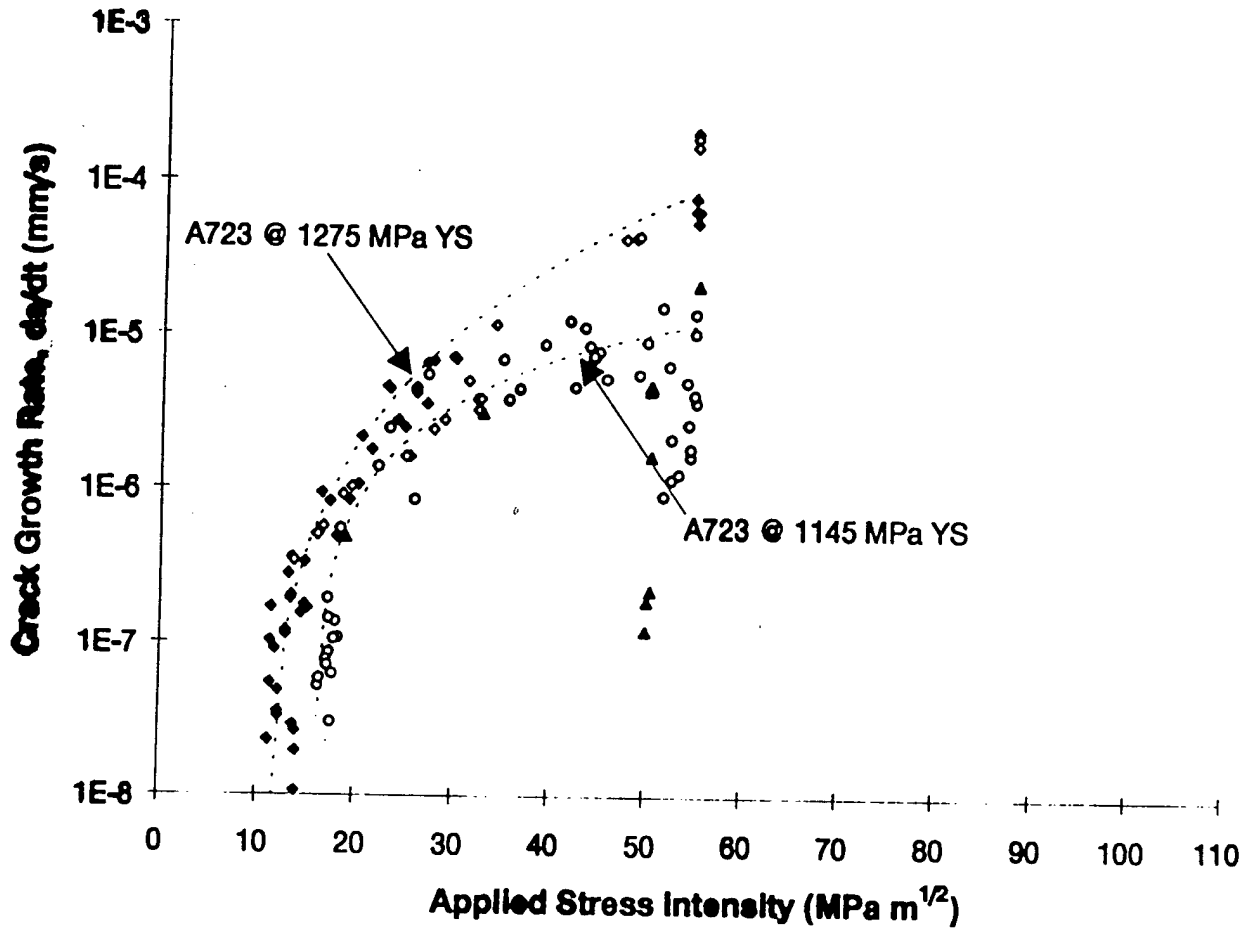
## ACID CRACKING RESULTS

$K_{APPLIED}$  VERSUS TIME FOR A723 STEELS



## ACID CRACKING RESULTS

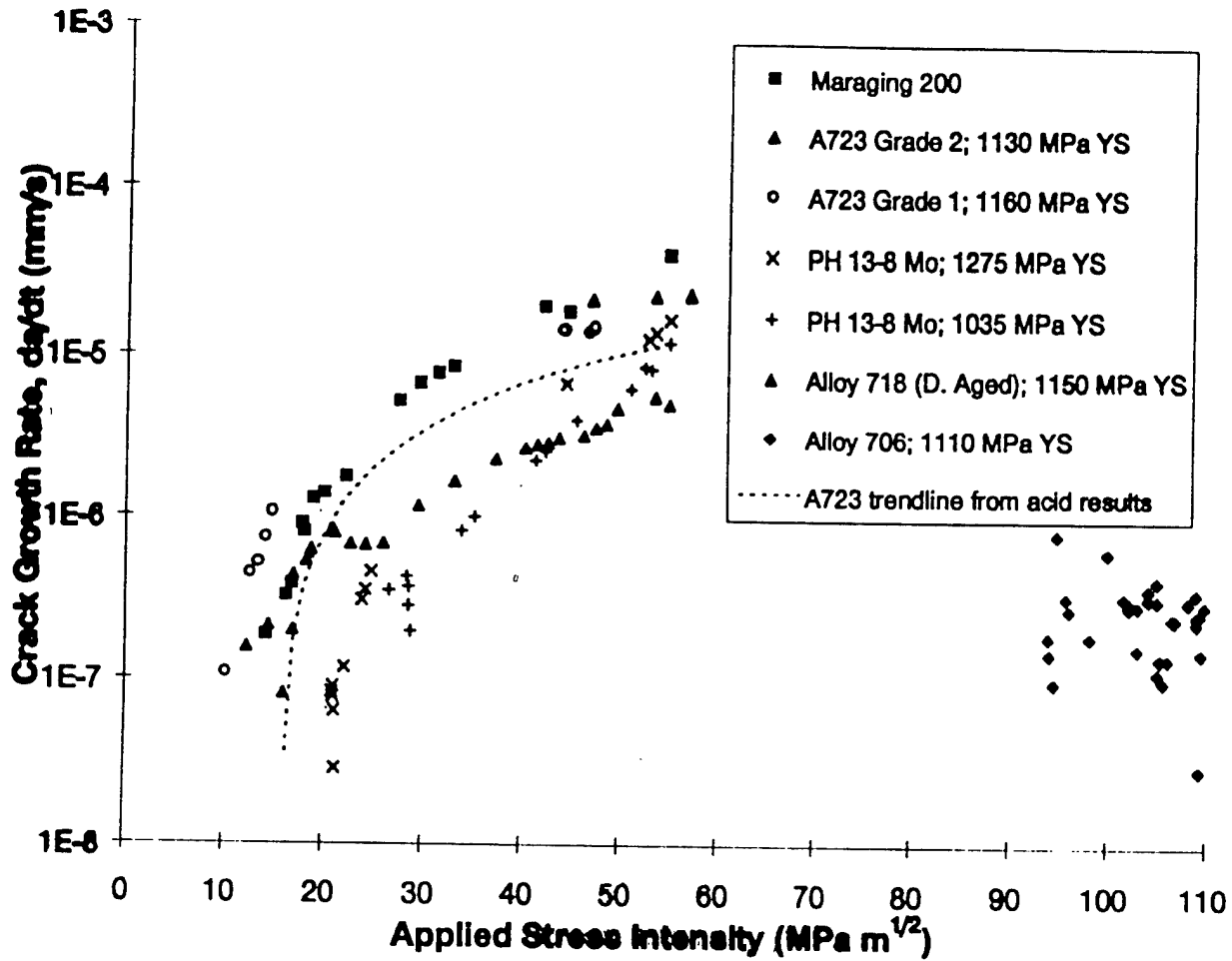
da/dt VERSUS  $K_{APPLIED}$  FOR A723 STEELS





# ELECTROCHEMICAL CELL RESULTS

da/dt VERSUS  $K_{APPLIED}$



## Task 1: Hydrogen Cracking Tests

### Activity 5: J-integral Fracture Toughness Test Procedures

USA-Army Benet Laboratory-ARDEC

J-integral fracture toughness test procedures for weld applications are being investigated with emphasis on simplified test methods suitable for small specimens cut from welds.

Results: Measurements of J<sub>ic</sub> fracture toughness for cleavage in as welded AISI 4130 steel HAZ have been made for applications to armament components.

Plans: Dynamic J<sub>ic</sub> tests will be conducted on A723 steel as part of ASTM round robin study.

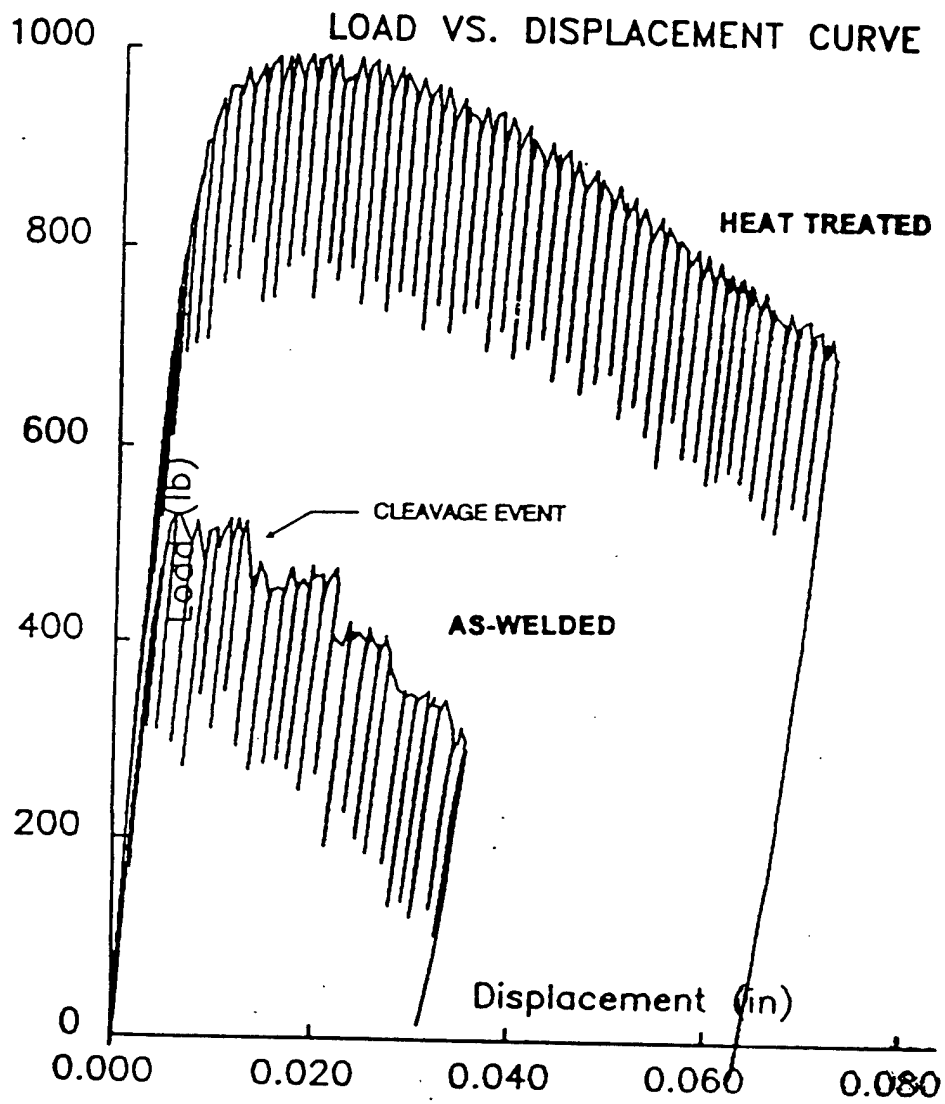
Status: in progress

Completion: 1998, Q3

previously

Task 4  
Activity 5

**J. TEST CONDUCTED ON AN AS DEPOSITED AND  
HEAT TREATED WELD**



## Task 1: Hydrogen Cracking Tests

### Activity 6: Fatigue Life Analysis in Hydrogen Environments

USA-Army Benet Laboratory-ARDEC  
UK-Univ. of Cranfield

A new analysis has been described for characterising fatigue life, including local stresses and initial crack. This work is being conducted jointly with U. Parker (Univ. of Cranfield, U. K.).

Results: "Fatigue Intensity Factor" concept shows significant effect of hydrogen environment on fatigue life of high strength steel armament structures.

Plans: Test and analysis is in progress. The results will be reported at the 9th International Conference on Fatigue, April 1997.

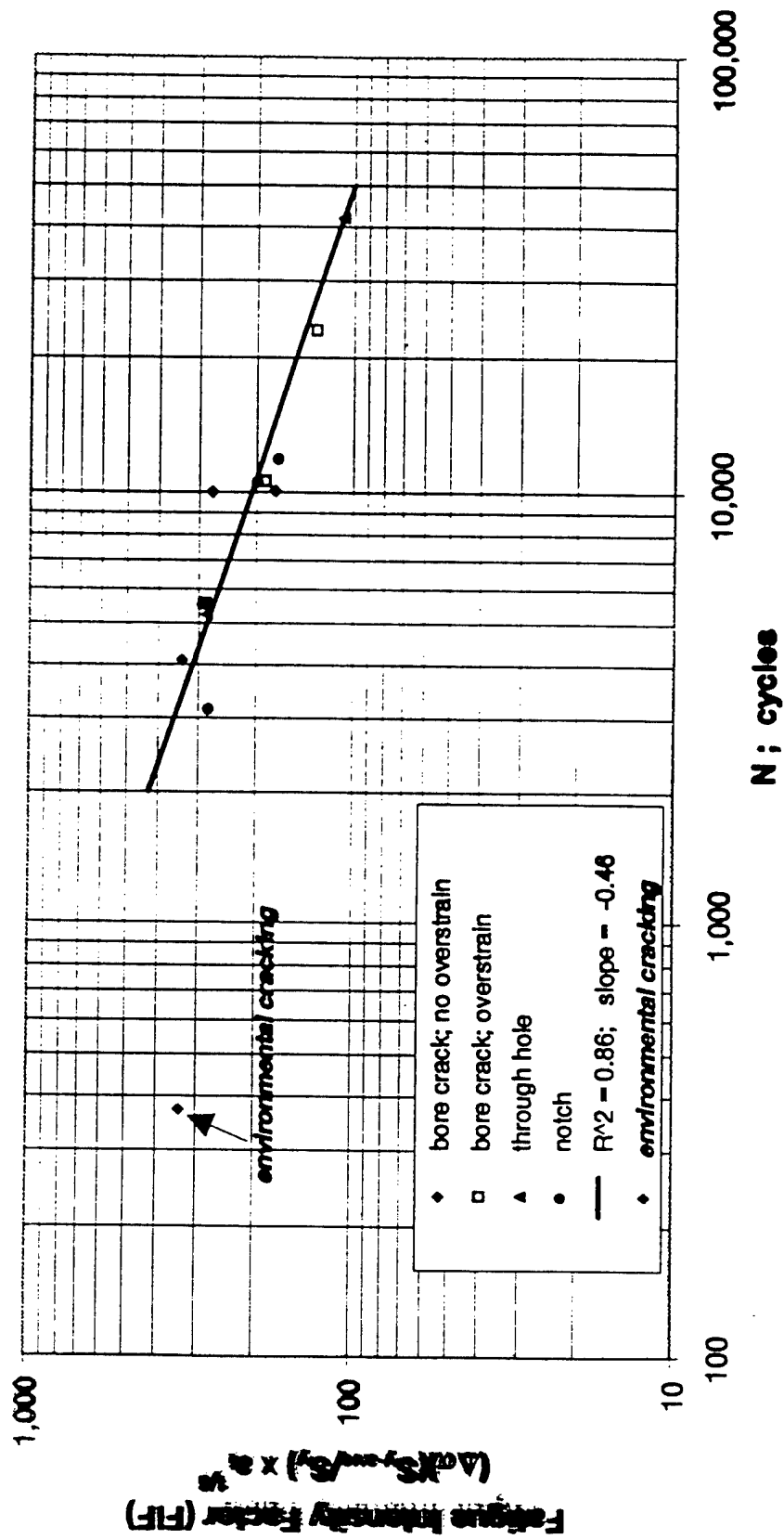
Status: in progress

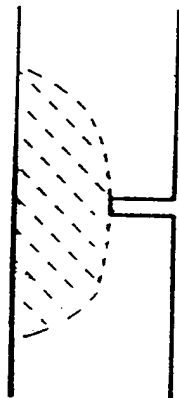
Completion: 1997, Q3

previously

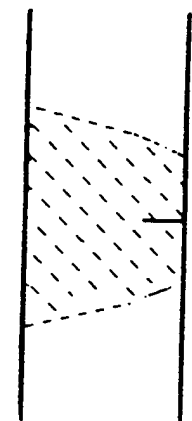
Task 4  
Activity 6

# FATIGUE INTENSITY FACTOR

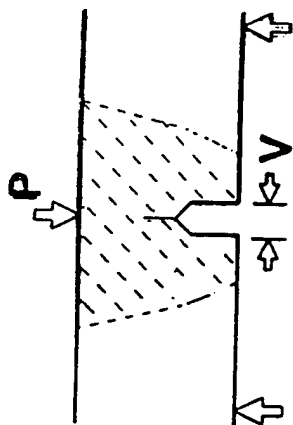




### S/N FATIGUE LIFE



### FATIGUE CRACK GROWTH

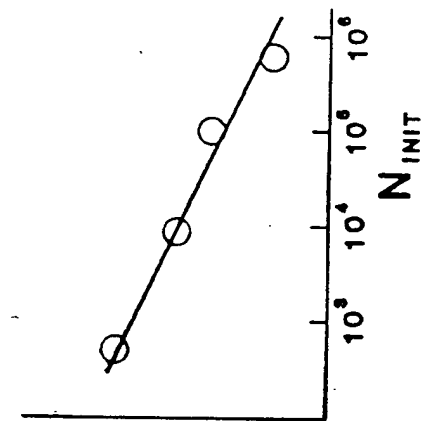


### FRACTURE TOUGHNESS

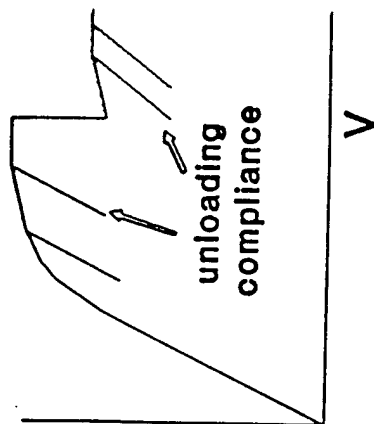
$K / \sqrt{r}$

$$da/dN = C (\Delta K)^3$$

$$N_{GROW} = \frac{[1/\sqrt{a_i} - 1/\sqrt{a_f}]}{\text{const} [1/\Delta S]^3}$$



$P$  P-V plot for J tests



Task 1: Hydrogen Cracking Tests

Activity 7: To Survey The Worst Case Scenarios for Hydrogen Cracking  
in Fabrication

Australia-DSTO  
Australia-ASC  
USA-NSWCCD

As a basis for determining the most appropriate test procedure, descriptions of worst case scenarios for hydrogen cracking in fabrication are being sought.

Results: A new initiative which has much cooperative interest among group members.

Plans: Descriptions are being requested and will be circulated for comment.

Status: initiated

Completion: 1997, Q4

## Standardisation of Laboratory Welding Tests

- first pass is preheat free
- the test piece has then been heated for subsequent passes
- trade off
  - allow specimen to cool=> increase diffusion time for H removal
  - weld without delay=>less time for H removal but different microstructures
  - hydrogen build up not as severe
  - full scale structure cooling rates are higher



## Task 1: Hydrogen Cracking Tests

### Activity 8: Development of Testing Criteria for Weld Repair

Australia-DSTO

Australia-ASC

The progressive aging of existing Naval platforms has necessitated the development of hydrogen cracking tests for weld repair. This condition potentially represents a worst case scenario for hydrogen cracking susceptibility.

Results: A new initiative which has much cooperative interest among group members.

Plans: Identify the worst case weld repair scenarios on Naval structures and develop a test plan which will evaluate the various hydrogen cracking testing procedures to assess these repairs.

Status: initiated

Completion: 1997, Q4

## Task 1: Hydrogen Cracking Tests

### Activity 9: Modelling of Electronic Bonding of Hydrogen in the Zone Ahead of Sub-critical Crack in (BCC) Ferrous Alloys

USA-Army ARL  
USA-CSM  
Australia-DSTO

This investigation will determine the relative energies of interstitials which can migrate to the zone of sub-critical crack in ferrous alloys. It will characterize the intra planar bonds when interstitials are present (e.g. establish if these interstitials change the nature of these bonds promoting/hindering crack tip propagation in the zone).

Results: There is evidence from prior calculations ( CSM - Mark Eberhart) that much understanding can be determine as to the nature of hydrogen damage from these fundamental atomic scale calculations.

Plans: Establish a research team of internationally respected investigators, both theoretical and experimental scientists, and propose the scope and work statements for this project to be submitted to the appropriate funding agencies. Dr. Genrich Krasko, US Army Research Laboratory was proposed as primary Principal Investigator.

Status: Initiated

Completion: 1999, Q2

## **SECTION V**

### **TASK 2**

#### **Influence of Welding Parameters and Hydrogen Content on Hydrogen Cracking**

## TASK 2

### INFLUENCE OF WELDING PARAMETERS AND HYDROGEN CONTENT ON HYDROGEN CRACKING

1. The Relationship Between Hydrogen Content and Susceptibility to Hydrogen Cracking  
Australia-DSTO
2. Hydrogen Cracking and Heat Input  
Australia-DSTO
3. Risk Evaluation of Hydrogen Cracking  
Australia-DSTO
4. Hydrogen Arc Sensing and Modelling to Predict Weld Metal Hydrogen Content  
USA-NSWCCD  
USA-Penn. State Univ.
5. Modeling of Hydrogen Cracking Behavior in a Repair Weld  
Canada-DREA
6. Use of Electrotransport to Reduce the Diffusible Hydrogen Content  
USA-CSM
7. Characterization of Undermatched Weldments  
USA-NSWCCD  
Australia-DSTO

Task 2 Determine Relationship Between Welding Parameters (hydrogen content) on Multiple Pass Weld Transverse Cracking

Activity	Status	Results	Description	Organisation
1. Hydrogen -induced subcritical cracking	in progress	Technique has been developed to determine relationships for ultrahigh strength steels	An experimental approach is proposed which promises to deliver fundamental information regarding the relationship between the hydrogen-induced sub-critical crack growth rate and both microstructures and diffusible hydrogen content. Presently working on deposits from E120S filler metal.	Aust. - DSTO
2. Hydrogen cracking and heat input	in progress	higher heat input welds crack at lower hardness	The influence of heat input on hydrogen cracking has been investigated for a submerged arc consumable. The resistance to hydrogen cracking increase with heat input. The hardness at which hydrogen cracking occurred decreased with the heat input.	Aust. - DSTO
3. Risk evaluation of hydrogen cracking	completed	No significant evidence of cracking	An experimental submarine section, which was welded using wide range of welding procedures, was evaluated as to the risk of hydrogen cracking.	Aust. - DSTO
4. Hydrogen arc sensing and modelling to predict weld metal hydrogen content	in progress	Model is being developed to allow prediction of weld metal hydrogen content	The arc sensing model will be extended to determine weld pool shape and time-temperature profiles associated with GMA welding. Currently, relationships between weld metal microstructures and toughness are being established. Hydrogen distribution and migration from the welding plasma to the solidified weld metal is being modelled. The model is being developed for GMA welding and will incorporate feed metal and resulting papilla characteristic of GMAW. The model utilised spectrographic data supplied by the hydrogen sensor to establish the initial hydrogen species in the plasma.	USA - NSWCCD

Task 2 (continued) Determine Relationship between Hydrogen Content and Multipass Weld Transverse Cracking

Activity	Status	Results	Description	Organisation
5. Modelling of hydrogen cracking behaviour in a repair weld	initiated	high group interest in project	Determination of the length of time necessary after repair welding before inspection for hydrogen cracking should be performed	Canada - DREA
6. Eliminate Post weld heat treatment by a electrotransport practice	in progress	with use of homopolar generator it may be possible to treat thick section materials	The concept of using electrotransport to reduce diffusible hydrogen levels was evaluated using transport calculations. The application of electrotransport during the welding thermal cycle may be useful in reducing hydrogen cracking susceptibility in large structural components.	USA - CSM
7. Characterisation of undermatched weldments	initiated	potential for reduction or elimination of preheat	The use of undermatching weld metal may improve productivity of welding high strength steels by reduction or elimination of preheat	US - NSWCCD

Task 2; Influence of Welding Parameters and Hydrogen Content on  
Hydrogen Cracking

Activity 1: The Relationship Between Hydrogen Content and The  
Susceptibility to Hydrogen Cracking

Australia-DSTO

An experimental technique has been developed to determine the relationship between the hydrogen induced sub-critical crack growth rate and both the microstructural constituents and diffusible hydrogen content.

Results: The technique has been tried successfully using an ultra high strength steel.

Plans: The trial will be extended to include an E120S filler metal.

Status: in progress

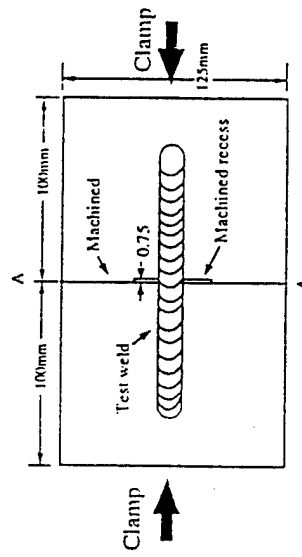
Completion: 1998, Q3

previously

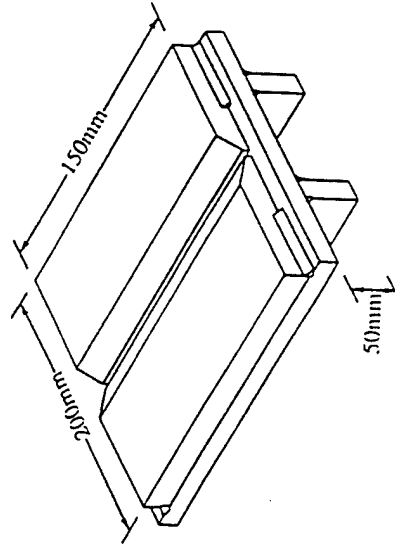
Task 67  
Activity 1

- X Known Stress Intensity
- X Known Hydrogen Concentration
- X Constant Microstructure

### Gapped Bead on Plate



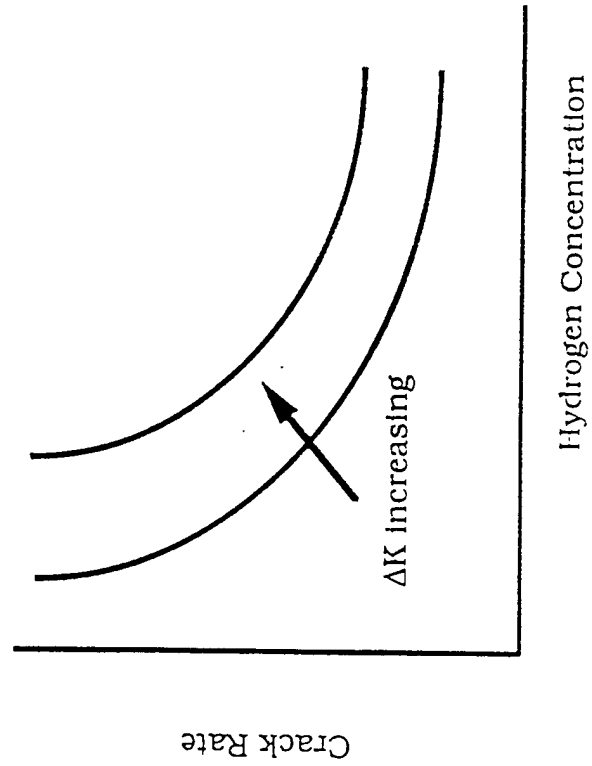
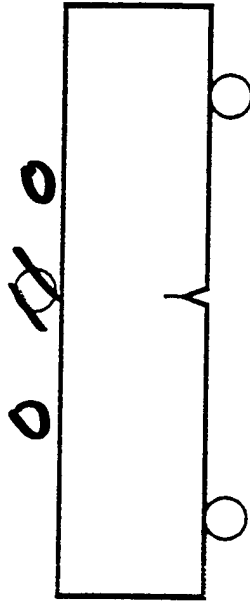
### Longitudinal Restraint Cracking





## Controlled Cracking Approach

- ✓ Known Stress Intensity
- ✓ Known Hydrogen Concentration
- ✓ Constant Microstructure



Task 2: Influence of Welding Parameters and Hydrogen Content on  
Hydrogen Cracking

Activity 2: Hydrogen Cracking and Heat Input

Australia-DSTO

The influence of heat input on hydrogen cracking has been investigated for a submerged arc consumable.

Results: The resistance to hydrogen cracking increases with heat input. The hardness at which hydrogen cracking occurred decreased with the heat input.

Plans: work continuing

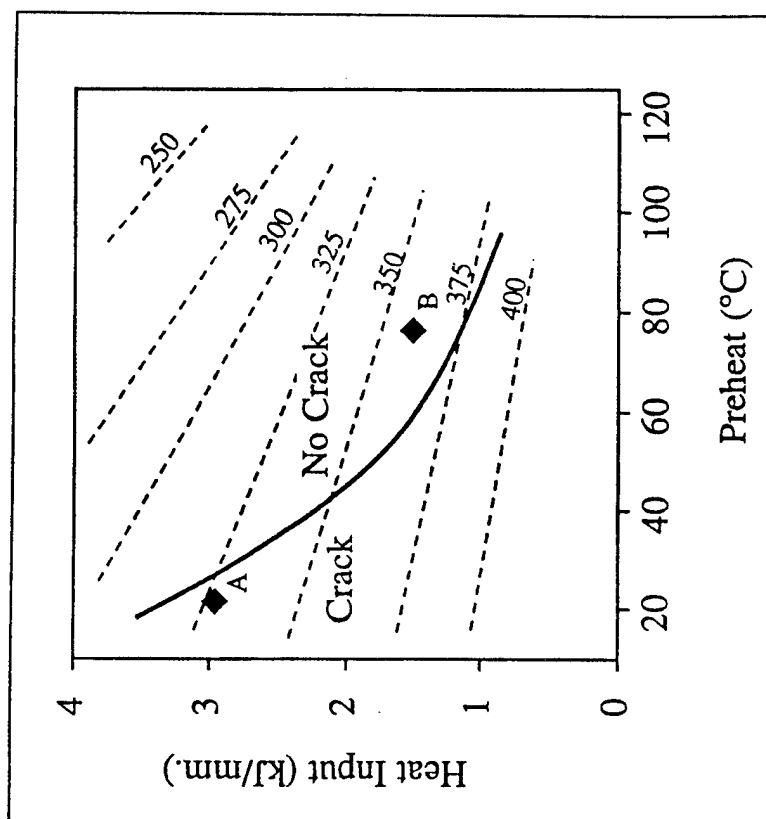
Status: in progress

Completion: 1998, Q3

previously

Task 67  
Activity 3

## Cracking and Hardness As Functions of Welding Parameters



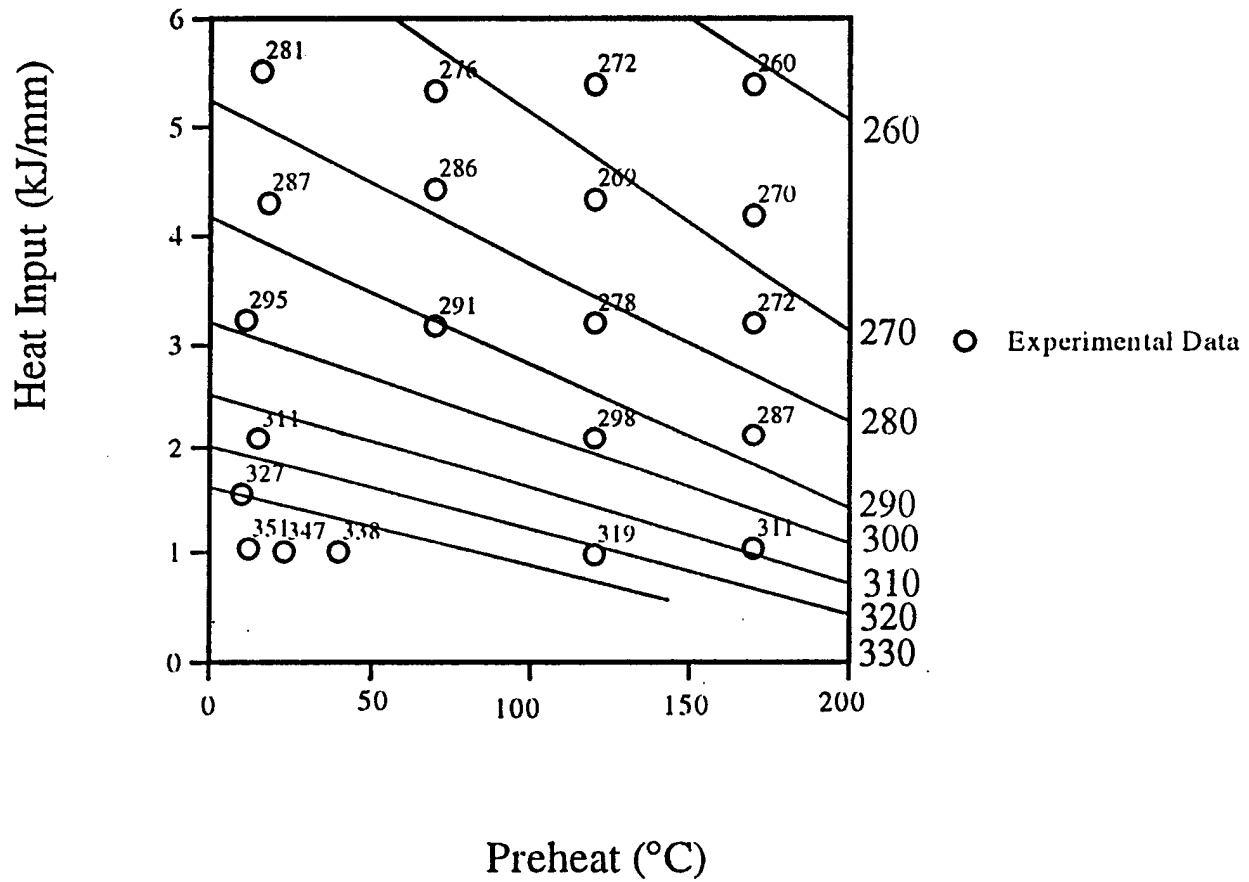
- “A” HV=330

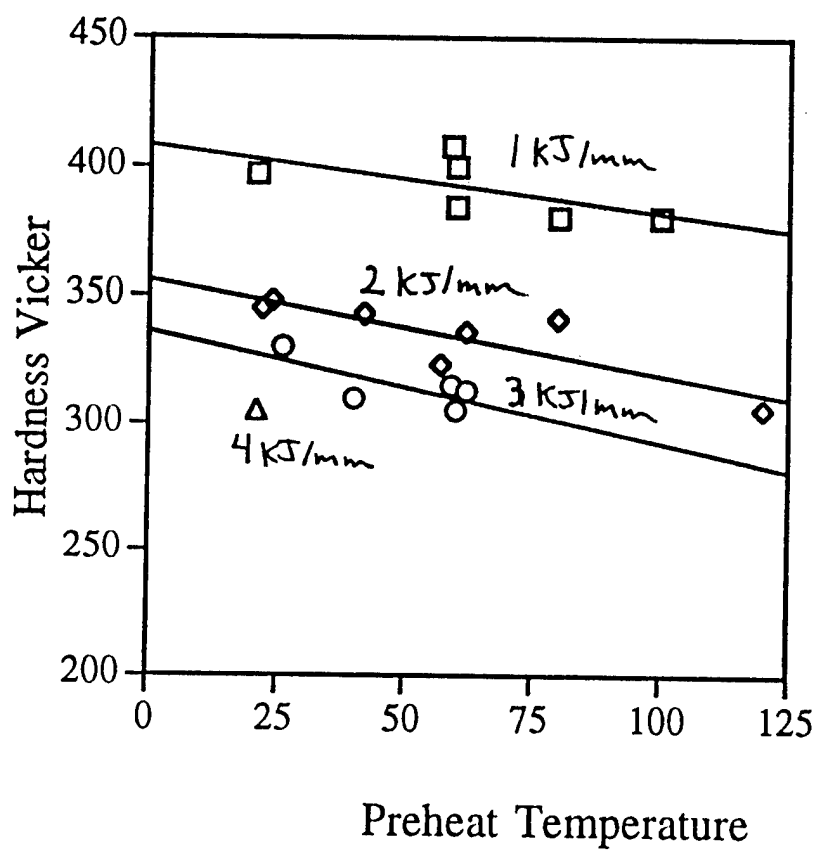
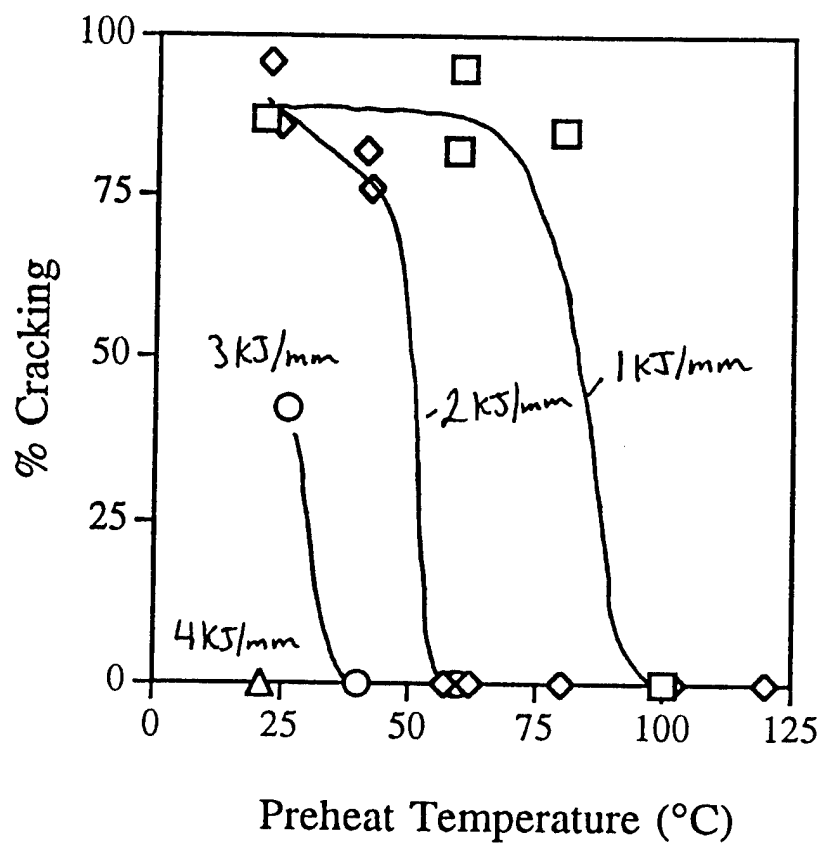
- “B” HV=360

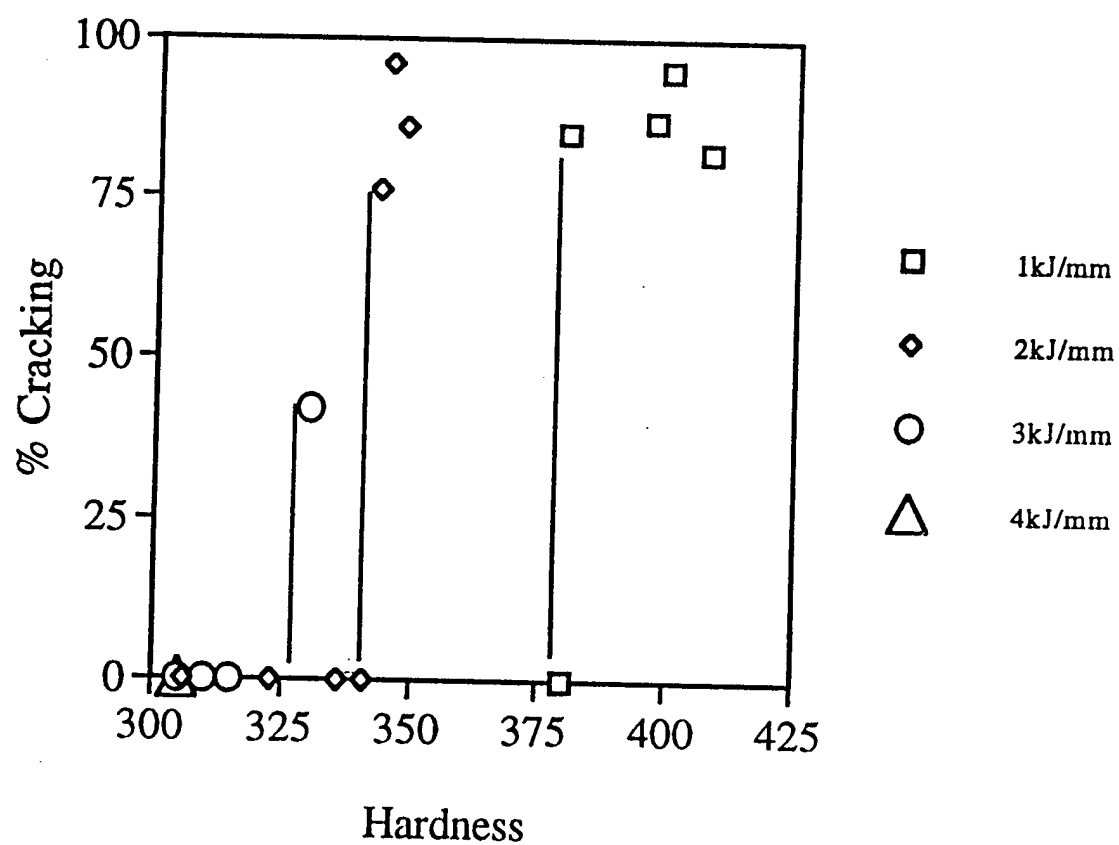
- Cracking occurs at “A”  
but not at “B”

Contours calculated on basis of empirical fit to data

$$H_v = (350.6 - 0.244T) \cdot HI \cdot (1.86 \times 10^{-4} T - 0.13328)$$







## Task 2: Influence of Welding Parameters and Hydrogen Content of Hydrogen Cracking

### Activity 3: Risk Evaluation of Hydrogen Cracking

#### Australia-DSTO

Control of weld metal hydrogen cracking in a 690 MPa yield strength steel during Australian submarine construction is an essential requirement. To evaluate the risk of hydrogen cracking and embrittlement, an experimental submarine section (7.8 m diameter, 2.4 m long, containing five stiffening ring frames) was fabricated using "high" carbon equivalent electrodes ( $P_{cm} = 0.283$  versus typical values of 0.26) and a wide range of welding procedures. The effect of carbon content on cracking risk was also examined. The welds were examined both non-destructively and destructively.

Results: No significant evidence of cracking was found. An increase in carbon content from 0.07 to 0.10 wt. Pct. was found to have little effect on yield stress. Assessment of welds in a test fabrication showed that a wide range of techniques and procedures can be used without a risk of cracking.

Status: completed

previously

Task 67  
Activity 4

## Observations:

From analysis of the yield stress data provided by weld procedure qualification records for 690 MPa steels:

- 1/ Considerable scatter in yield stress value may occur when welding with the same nominal welding electrodes
- 2/ The scatter in results cannot be attributed to minor variations in weld metal carbon content.
- 3/ For identical consumables and welding procedures, reproducibility of tensile test results is not good
- 4/ Examination of welds on a test can and routine inspection of welds on the submarines has revealed little evidence of cracking
- 5/ Noting that:
  - a) the formulae were developed as a measure of *parent metal hardenability*, and
  - b) the random scatter in yield stress results is sufficient to swamp the effect of minor variations in filler metal composition,this work casts doubt on the validity of using conventional carbon equivalent formulae *alone* for the assessment of crack sensitivity,



## Risk Evaluation

- 1/ Four out of 188 procedures gave yield stress values over 900 MPa.
- 2/ Two of the four were used
- 3/ Both of these gave high elongations and an AF microstructure
- 4/ Re-testing of these welding procedures gave significantly lower yield stress values
- 5/ A wide range of welding techniques were used on the COLLINS practice can and negligible evidence of cracking was found
- 6/ Isolated examples of cracking have been found during fabrication. These have been investigated to identify the cause of cracking and all have been repaired

Task 2: Influence of Welding Parameters and Hydrogen Content on  
Hydrogen Cracking

Activity 4: Hydrogen Arc Sensing and Modelling to Predict Weld  
Metal Hydrogen Content

USA-NSWCCD

USA-Penn. State Univ.

The arc sensing model will be extended to determine weld pool shape and time-temperature profiles associated with GMA welding. Currently, relationship between weld metal microstructures and toughness are being established.

Hydrogen distribution and migration from the welding plasma to the solidified weld metal is being modeled. The model is being developed for GMA welding and will incorporate feed metal and resulting papilla characteristic of GMAW. The model utilised spectrographic data supplied by the hydrogen sensor to establish the initial species in the plasma.

Results: Hydrogen emissions data was used to predict diffusible hydrogen test results using the Penn. State Univ. model. A cylindrical heat source has been developed for model development. The cylindrical heat source produced a papilla consistent with GMAW.

Plans: The weld pool shapes and resulting thermal profiles will be validated. The effect of variations in welding parameters will be evaluated.

Status: in progress

completion: 1997, Q3

previously

Task 67  
Activity 5

## Task 2: Influence of Welding Parameters and Hydrogen Content on Hydrogen Cracking

### Activity 5: Modeling of Hydrogen Cracking Behavior in Repaired welds

#### Canada-DREA

The question of how long after repair welding inspection for hydrogen cracking should be delayed is being examined by modeling and experiments. Dr. Lalit Malik of Fleet Technology and Dr. Brian Graville of Graville Associates have received a DREA research contract to address this question. Numerical modeling is being done to estimate the temperature history, hydrogen diffusion/distribution and thermal/residual stresses generated as a result of a multipass repair weld. Experiments are being done to determine the critical local hydrogen concentration for causing cracking for a given stress and microstructure. Essentially the experiments will allow the model to be calibrated for crack prediction. Experiments and modeling will focus on 9 mm thick A517 grade F steel, welded with E11018 electrodes. The critical hydrogen content for causing cracking for a give stress and hydrogen content will be determined by: placing a Charpy V notch in the heat affected zone of a multipass single V weld; gouging out part of the top of the weld, and rewelding, (simulating a repair weld); heat treating, if necessary, to cause some redistribution of hydrogen; and loading the specimen and determining if and when, crack growth occurs.

Results: High group interest in this project. Work in progress.

Plans: work in progress

Status: in progress

Completion: 1998, Q2

## Task 2: Influence of Welding Parameters and Hydrogen Content on Hydrogen Cracking

### Activity 6: Use of Electrotransport to Reduce The Diffusible Hydrogen Content

#### USA-CSM

The concept of using electrotransport to reduce diffusible hydrogen levels was evaluated using transport calculations.

Results: The application of electrotransport during the welding thermal cycle may be useful in reducing hydrogen cracking susceptibility in small technical assemblies that might otherwise experience distortion or unacceptable microstructural changes as a result of conventional post weld heat treatment.

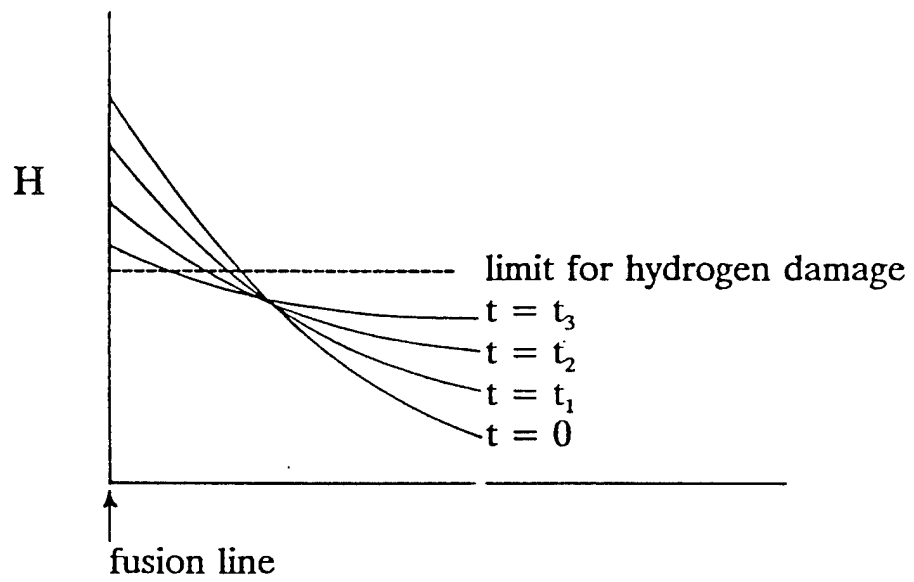
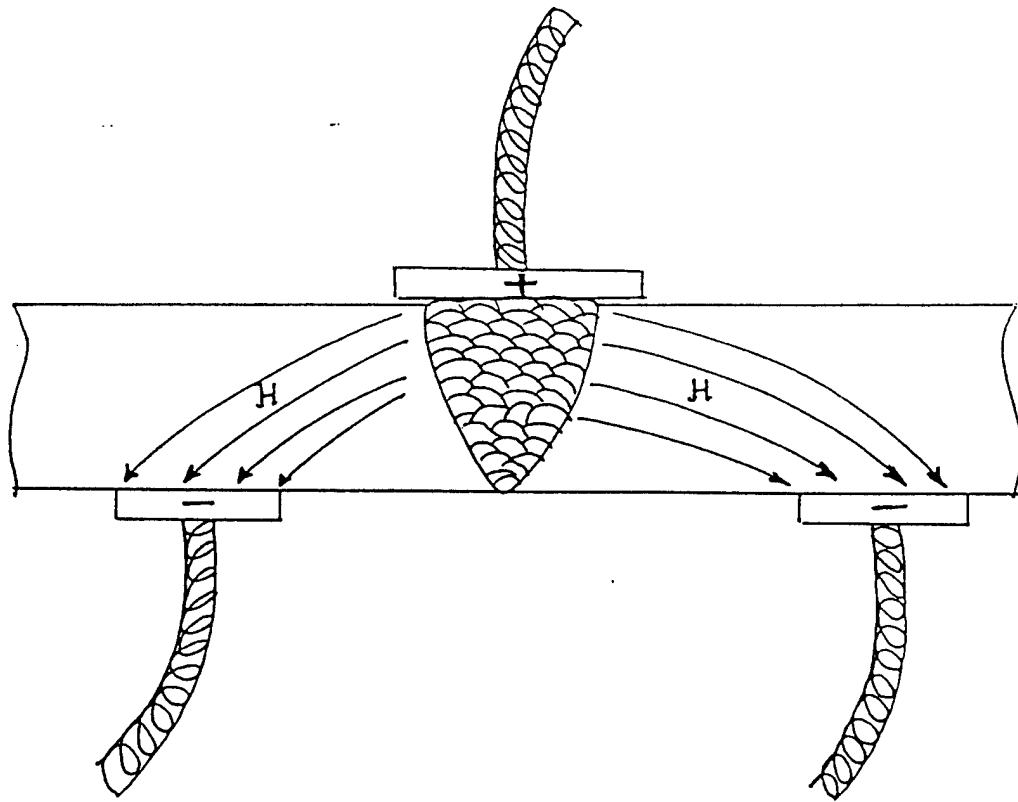
Plans: Due to the requirement of excessively high current, if electrotransport methods are to be applied to heavy section weldments, this technique initially appeared useful for only small weldments such as those welds found in precision assemblies. Discussions are in progress with the Center of Electromechanics of the Univ. of Texas to set up an industrial demonstration project to illustrate that homopolar power sources can produce sufficient current and are portable enough to work in combination with the welding practice associated with heavy section weldments.

Status: in progress

Completion: 1998, Q3

previously

Task A  
Activity 6



Task 2: Influence of Welding Parameters and Hydrogen Content on  
Hydrogen Cracking

Activity 7: Characterization of Undermatched Weldments

USA-NSWCCD  
Australia-DSTO

The use of undermatching weld metals may improve productivity of welding high strength steels by reduction or elimination of preheat.

Plans: The scope and work statements will be defined and work will proceed.

Status: initiated

Completion: 1998, Q4

## **SECTION VI**

### **TASK 3**

#### **Development of High Strength Steel Filler Metals**

### TASK 3

#### DEVELOPMENT OF HIGH STRENGTH STEEL FILLER METALS

1. Preheat Free MMA and FCA Welding Consumables  
Australia-DSTO  
Australia-CISRO-DMT
2. Development of ULCB Wires  
USA-NSWCCD
3. ULCB Wire Evaluation  
USA-NSWCCD
4. Evaluation of ULCB MCAW Consumables  
USA-NSWCCD
5. Use of Fluorine and Optimal Oxygen to The Welding Plasma to  
Assist in Hydrogen Management  
USA-CSM
6. Use of Austenite Decomposition Start Temperatures to  
Predict Weld Hydrogen Distribution and Cracking Behaviour  
USA-CSM  
USA-NSWCCD
7. MultiPass Weld Metal Properties  
  
Australia-CISRO  
USA-CSM
8. Use of Weld Metal Traps for Hydrogen Management  
USA-CSM
9. Analytical Methods to Evaluate Weld Hydrogen Distribution  
USA-CSM  
USA-SUNY Albany



Task 3 Develop High Strength steel filler metals to be used without preheat.

Activity	Status	Results	Description	Organisation
1. Preheat free MMA and FCA Welding Consumables	in progress	Consumables produced	The review of the status of preheat free consumables is continuing. Experimental MMA and FCA consumables, each at 2 different chemistry levels has been received from DMT/CSIRO, Adelaide.	Aust. - DSTO
2. Development of ULCB wires	in progress	welds have been fabricated with various shielding gases and thermal processing to produce various levels of oxygen, nitrogen and grain size.	Development of ULCB wires has shown that increasing the Ni content had a beneficial effect on impact toughness. Also decreasing inclusion volume fraction increased upper shelf energy and decreases 50% FATT.	USA - NSWCCD
3. ULCB wire evaluation	in progress	Several solid wires have met required specification	Mechanical property and weldability evaluations of ULCB weld deposits from specially designed wires are being determined	USA - NSWCCD
4. Evaluation of ULCB MCAW consumables	initiated	continuation of ULCB wire investigation	This task will evaluate 4 MCAW wires produced to meet weld deposit chemistries specified by NSWCCD	USA - NSWCCD
5. Fluorite additions to control weld hydrogen content	initiated	theoretical and experimental evidence indicates the possibility of obtaining low hydrogen contents	Use of fluorite and optimal amounts of oxygen introduced to the welding plasma to control weld hydrogen content is being evaluated.	USA - CSM
6. Austenite decomposition temperatures as hydrogen cracking indicator	in progress	preliminary results suggest value of using $M_s$ temperatures	MS temperatures was shown to delineate cracking tendencies of high strength steels in hydrogen environment. The difference in $M_s$ temperatures of base metal and weld metal can indicate whether cracking will occur in the weld or HAZ. The successful application of $M_s$ temperatures as a cracking induce results from the large differences in hydrogen solubility and diffusion coeff. between ferrite (martensite) and austenite.	US - CSM US - NSWCCD

7. Multiple pass weld metal properties cooperative project	in progress	AWS 96 (Chicago) fracture paper on multipass welds	A cooperative research project between CSIRO and CSM is in progress to better understand the influence of alloying additives on the microstructural and mechanical properties of weld metal for shielded arc welding processes. The work is proceeding at each institution and visitations have been made to share data, to discuss alloying and thermal processing models, and to design needed experiments.	Aust - CSIRO US - CSM
8. Reduction of diffusible hydrogen through the use of weld metal hydrogen traps	in progress	trapping elements selection has been completed and an experiment to evaluate this concept for hydrogen management is in progress	the use of weld metal hydrogen traps to reduce the available diffusible hydrogen content is being investigated.	US - CSM
9. Analytical method to evaluate weld hydrogen distribution	initiated	preliminary results using LIBS demonstrate the ability to measure weld hydrogen distribution	Laser Induced Breakdown Spectroscopy has been used to demonstrate that the weld hydrogen content is not uniform in its distribution but has localised high contents which should be of major concern to the integrity of high strength steel welds. These localised hydrogen contents are most likely the cause in the spread of the measured hydrogen cracking results in welds that have acceptably low measured diffusible hydrogen contents.	US - CSM

### Task 3: Development of High Strength Steel Filler Metals

#### Activity 1: Preheat Free MMA and Flux Cored Arc Welding Consumables

Australia-DSTO

Australia-CISRO-DMT

The review of the status of preheat free consumables is continuing. Experimental MMA and FCA consumables, each at two different composition levels has been received from DMT/CSRRO, Adelaide.

Results: The first batch of consumables has been received. The all weld metal compositions for the two FCA consumables were:

Elements (wt, pct.)	A (600-690 MPa yield)	B (700-800 MPa yield)
C	0.04	0.04
Mn	1.6	1.01
Si	0.16	0.17
Ni	2.9	5.6
Mo	0.54	0.73
Ti	0.004	0.005
Cr	0.01	0.27
Al	0.009	0.011

Plans: Evaluation of weld metal properties, viz all weld metal tensiles, transverse tensiles, Charpy toughness and metallography is about to commence. The next stage involves a new iteration of consumable compositions after discussions with NSWCCD. Obtaining core material of very low carbon content (0.02 wt, pct.) has been identified as a critical issue and this need will be pursued concurrently with the new iteration of compositions.

Status: in progress

Completion: 1997, Q3

previously

Task A

Activity 1

## TASK A : "PREHEAT FREE WELDING CONSUMABLES

- Review status of "preheat free" high strength welding consumables
- Identify supplier, and obtain experimental quantities of MMA and FCAW consumables

Ship Structures and Materials  
Division

DSTO

# “PREHEAT FREE” CONSUMABLES

Target Yield Strength (MPa)	Target Chemistry					
	C	Mn	Si	Ni	Mo	Ti Cr Al
600 - 690	0.02	1.6	0.25	2.65	0.50	0.005 alap alap
700 - 800	0.02	1.0	0.25	5.50	0.70	0.005 0.25 alap

alap = as low as possible

Ship Structures and Materials  
Division

# “PREHEAT FREE” WELDING CONSUMABLES

Actual compositions: 1.2 mm diameter flux cored arc consumables

Target Yield Strength (MPa)	Actual Chemistry					
	C	Mn	Si	Ni	Mo	Ti    Cr    Al
600 - 690	0.04	1.6	0.16	2.9	0.54	0.004 0.01 0.009
700 - 800	0.04	1.01	0.17	5.6	0.73	0.005 0.27 0.011

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Division

# “PREHEAT FREE” WELDING CONSUMABLES

Actual compositions minor elements: 1.2 mm diameter flux cored  
arc consumables

Target Yield Strength (MPa)	S	P	Cu	V	Nb	B
600 - 690	0.010	0.016	0.03	0.007	0.001	<0.0005
700 - 800	0.010	0.017	0.04	0.007	0.002	<0.0005

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# **“PREHEAT FREE” WELDING CONSUMABLES**

**Next Stage: For FCA and MMA**

**Weld metal properties:**

- All weld metal tensiles
- Transverse tensiles
- Charpy toughness
- Metallography

**Ship Structures and Materials  
Division**

**DSTO**



# “PREHEAT FREE” WELDING CONSUMABLES

## Future work:

- Next iteration of experimental FCA and MMA consumables after discussions with NSWC
- Obtain low carbon core material for:
  - FCA - 12 mm wide and 0.04 mm thick
  - MMA - 3.2 and 4.0 mm diameter rod

### Task 3: Development of High Strength Steel Filler Metals

#### Activity 2: Development of Ultra Low Carbon Bainite (ULCB) Wires

USA-NSWCCD

Development of ULCB wires has been shown that increasing the nickel content had a beneficial effect on impact toughness. Also these materials decrease the inclusion fraction, increase the upper shelf energy and decrease 50% FATT.

Results: Welds have been fabricated with various shielding gases and welding thermal cycles to produce weld metal of various oxygen and nitrogen contents and grain sizes. Work is progressing in thoroughly characterizing these weld metals.

Plans: work in progress

Status: in progress

Completion: 1997, Q3

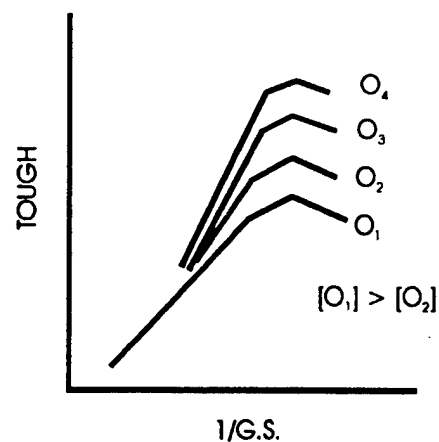
previously

Task A  
Activity 2,3

## RESULTS (Act.. 2)

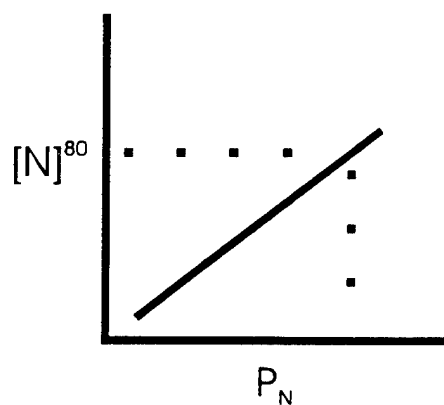
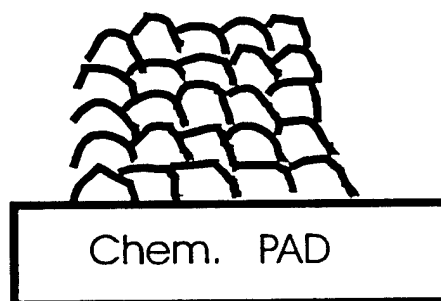
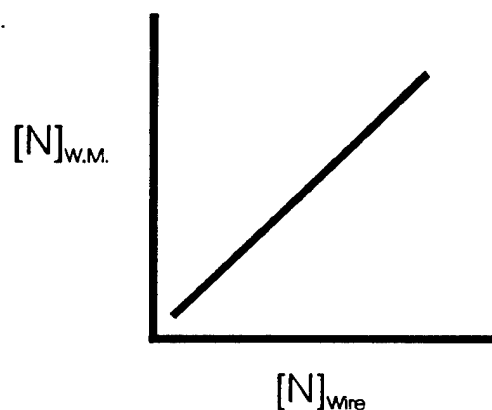
→ Evaluate effects of O and G.S.

→ M2, (200 ppm)      M5, (250 ppm)      M10 (440 ppm)



→ Thermal Cycle to Achieve Various G.S.  
A.W., 60 $\mu$ m, 30 $\mu$ m, 17 $\mu$ m

→ Evaluate Effects of N



## Development of ULCB Weldmetals

NSWC - Act. 2

Navy Wide - Act. 5

Evaluation of Hobart Wires

- from Act. 3

- Add New

### PARTICIPANTS

NSWC, EB, CTC, OGI, ESAB, HOBART, LINCOLN, NRL, NNS

### REQUIRMENTS

- 82\* min. Y.S. - HY or HSLA-80 - NAS

- 88\* min Y.S. - HY or HSLA-100 - Aircraft Carrier

- 35 ft-lbs @ -60°F\*

- 60 ft-lbs @ 0°F\*

- No Preheat

- \* 5-100°F/s @ 1000°F

### Task 3: Development of High Strength Steel Filler Metals

#### Activity 3: Ultra Low Carbon Bainite Wire Evaluation

##### USA-NSWCCD

Several solid wires met the required properties. Some of the wires experienced hydrogen damage. The lean wire compositions are not meeting strength properties.

Results: work is in progress.

Plans: continuation of mechanical property and weldability evaluations. Determination of optimal chemical compositions using neural network analysis is in progress.

Status: in progress

Completion: 1997, Q3

## TEST MATRIX

WIRE-            LEAN      NOM.      RICH

PLATE-            HY80, HSLA80, HY100, HSLA100

<u>C.R.-</u>	3/8" PLATE	→	2" PLATE
	65 KJ/IN		30 KJ/IN
	300°F P&I		50°F P&I

## WIRE CHEMISTRY GOALS

C    ≤ 0.02%  
Mn  0.75-2.40%  
Mo  0.3-1.5%  
Ni  1.9-5.0%  
Nb  0-0.05%  
Cr  0-0.3%  
Ti  0-0.030%

## VIM

N < 10 ppm  
O < 120 ppm?

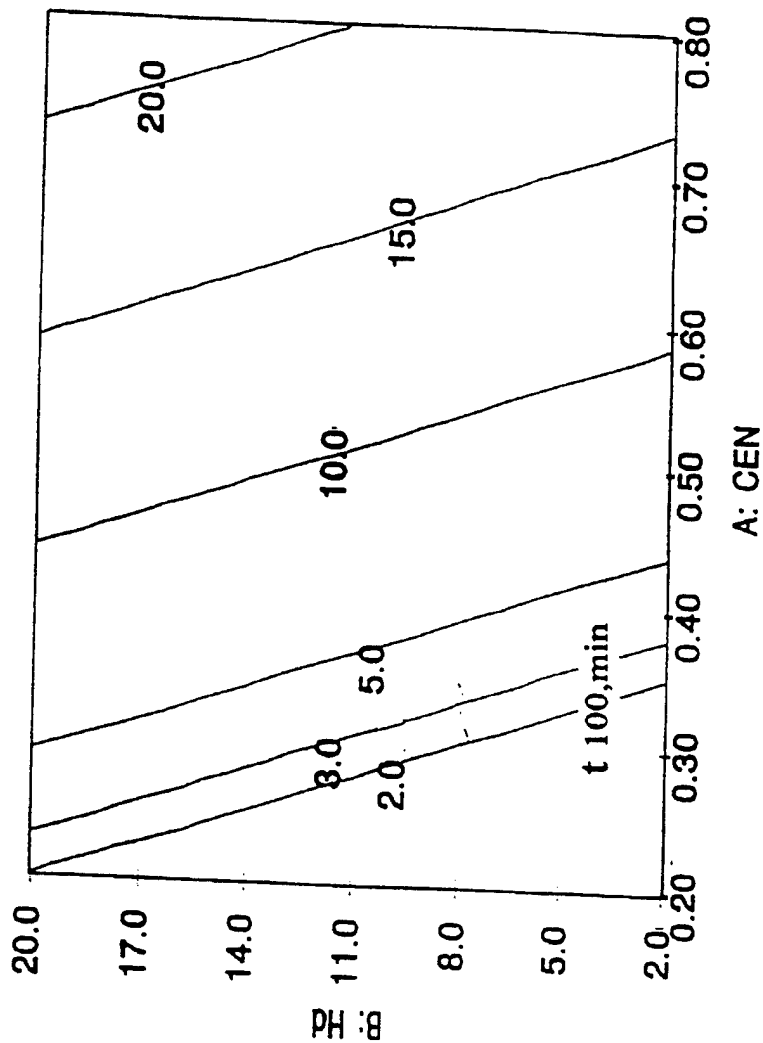
## RESULTS (Act. 5)

Solid Wires - Most Progress

Several met Targets:

- Ltec-N OK except  $< ^\circ\text{F/s}$   
low strength
- CTC-N- H Damage in 2" HSLA-100
- All lean chems. - Trouble meeting  $\sigma_y$
- WIC - 1" Thick  
CEN = 0.4, HD - 3.5 ml/100g - No Crack  
CEN = 0.45, HD - 4.0 ml/100g - Cracking
- Redefine Rich & Lean ?

# Iso-t<sub>100</sub>, min Contours of the Hydrogen Cracking Response Surface



$$t_{100\text{-min}} = 34.1 (\text{CEN}) + (\text{Hd} - 5) / 3.5 - 9.1$$

23 Oct 1996



Task 3: Development of High Strength Steel Filler Metals

Activity 4: Evaluation of ULCB MCA Welding Consumables

USA-NSWCCD

This activity will evaluate four MCA welding wires produced to meet weld deposit compositions specified by NSWCCD.

Results: work initiating

Plans: four selected MCA wire compositions will be prepared into welding wire and evaluated.

Status: initiated

Completion: 1997, Q3

### Task 3: Development of High Strength Steel Filler Metals

#### Activity 5: Use of Flourine and Optimal Oxygen Additions to the Welding Plasma to Assist in Hydrogen Management

USA-CSM

The use of selected flouride and oxide additions to welding consumables to promote a plasma chemistry that reduces the weld pool hydrogen content is being investigated.

Results: Effective use of the water and HF reactions in the plasma to reduce weld pool hydrogen content has been demonstrated. Various flouride additions are being added to the electrode covering and the resulting welds are being evaluated. Flourides are being carefully selected based on their physical stability and their predicted pyrochemical behaviour.

Plans: Further characterization of the influence of specific flouride additions on the resulting diffusible hydrogen content will continue. With the determination of the most promising flouride additions more extensive evaluation will be preformed to determine the optimum flouride content and weld metal oxygen content necessary for various sets of welding parameters.

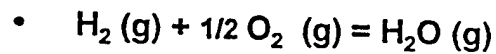
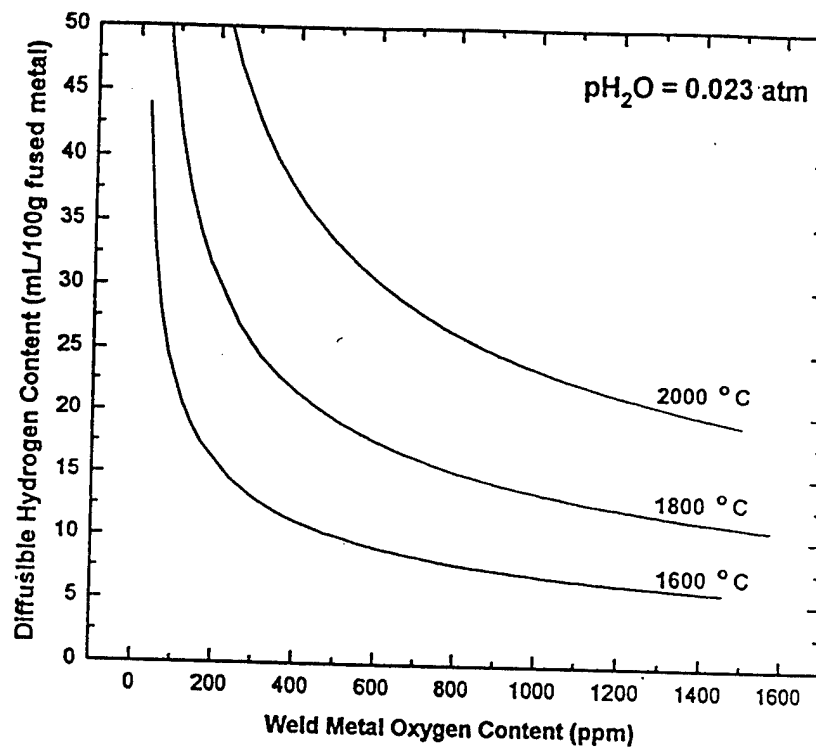
Status: in progress

Completion: 1998, Q3

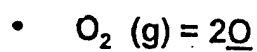
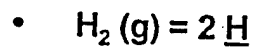
# Thermo-chemical Reaction in Arc Plasma

Hydrogen absorption control by hydrogen - oxygen reaction

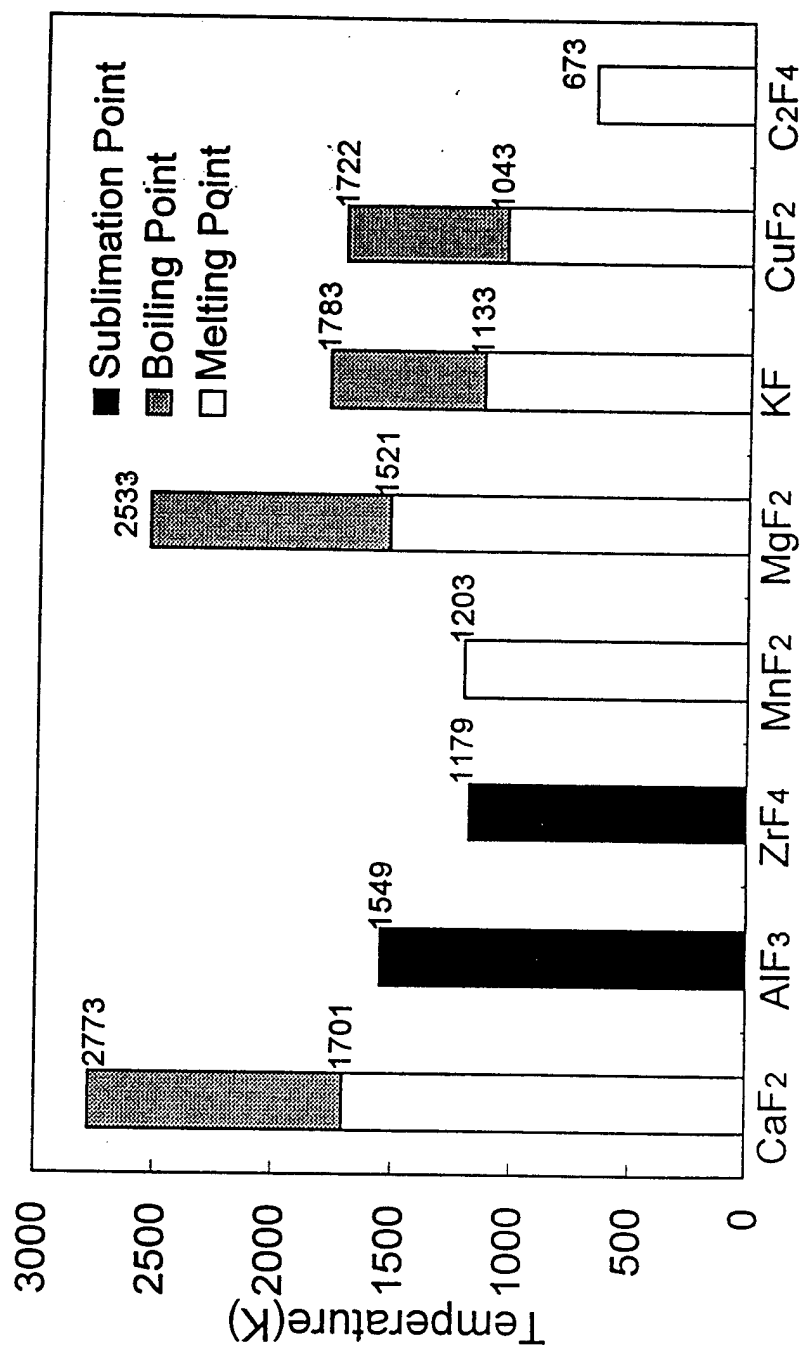
Weld Metal Hydrogen-Oxygen Relationship



- $k = \exp(-\Delta G^0 / RT) = \frac{P_{H_2O}}{P_{H_2}(P_{O_2})^{1/2}}$



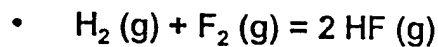
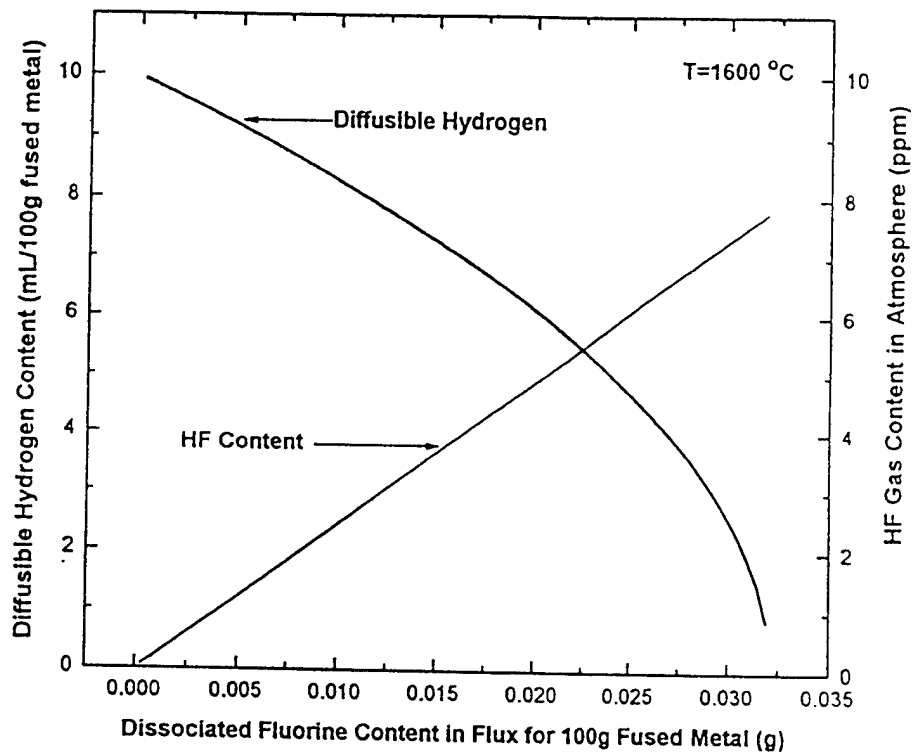
## Transition Points of Fluorides



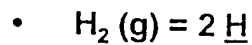
## Thermo-chemical Reaction in Arc Plasma

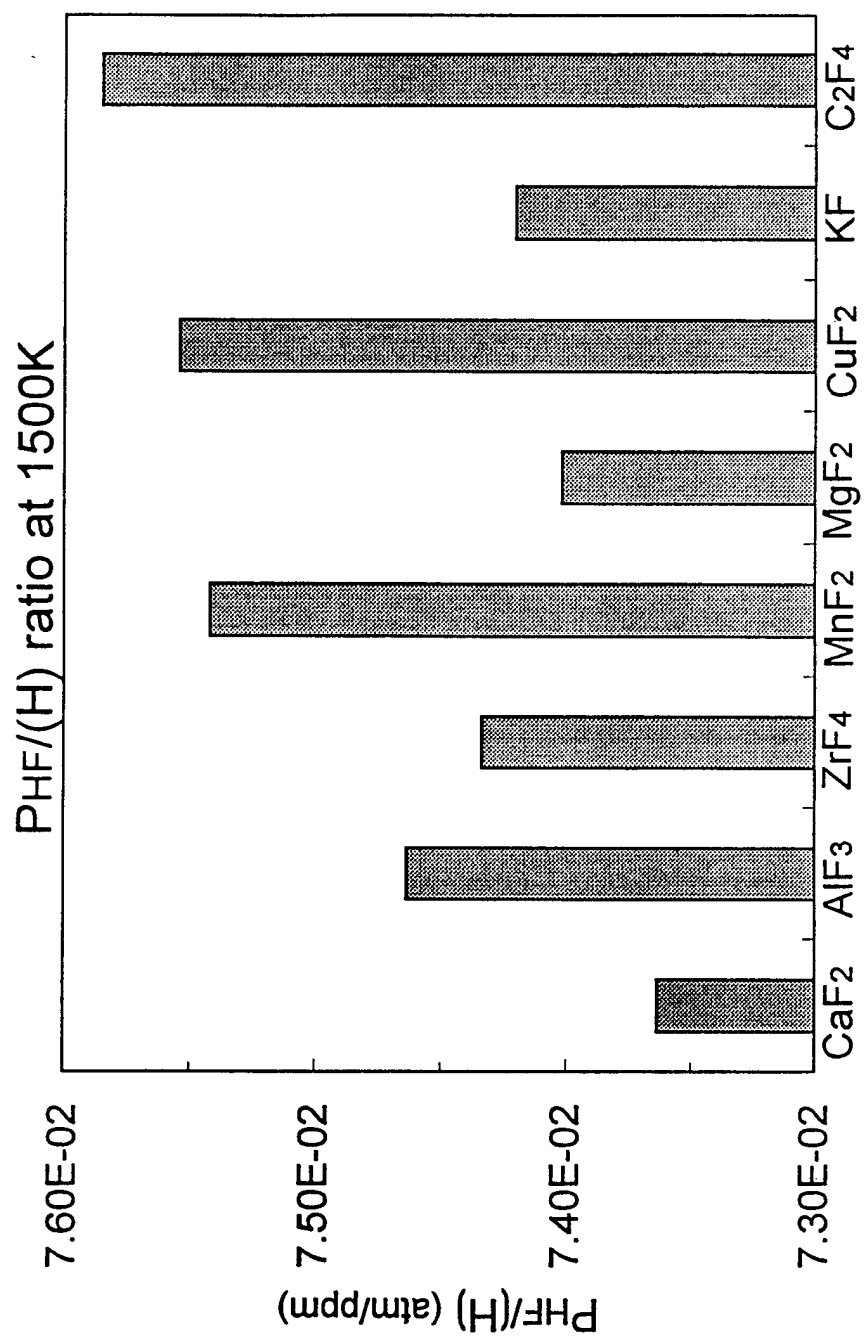
Hydrogen absorption control by hydrogen - fluorine reaction

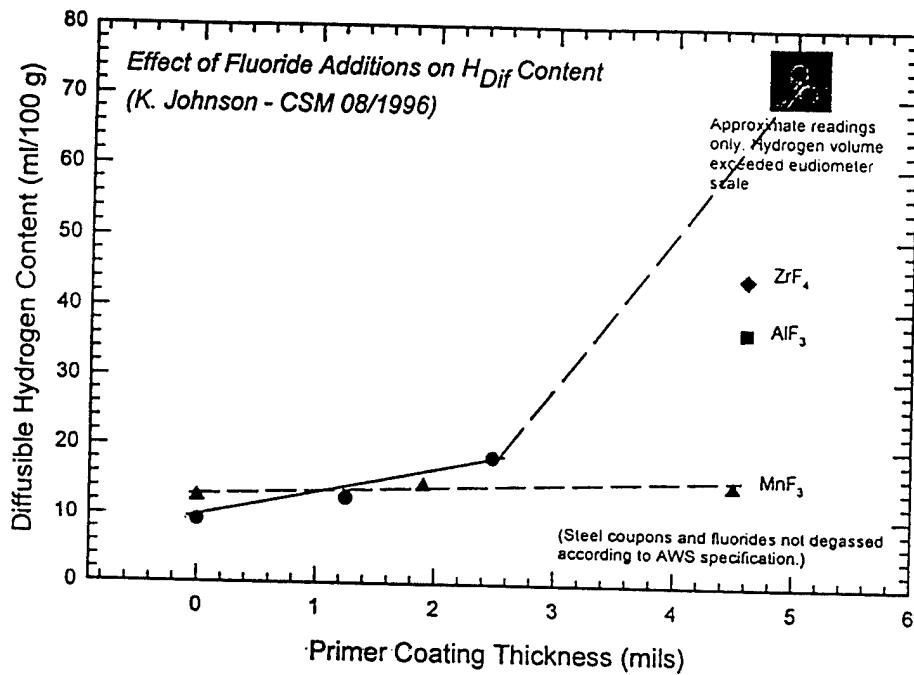
Weld Metal Hydrogen - Fluorine Relationship



- $k = \exp(-\Delta G^0 / RT) = \frac{(P_{\text{HF}})^2}{P_{\text{H}_2} \cdot P_{\text{F}_2}}$







Effect of fluoride additions on diffusible hydrogen content

### Task 3: Development of High Strength Steel Filler Metals

#### Activity 6: Use of Austenitic Decomposition Start Temperatures to Predict Weld Hydrogen Distribution and Cracking Behaviour

USA-CSM

USA-NSWCCD

A practice of comparing calculated austenitic decomposition start temperatures of the base metal and weld metal to predict the hydrogen distribution and cracking behaviour of high strength steel welds has been demonstrated. The practice uses the differences of the calculated martensite temperatures to predict whether cracking will occur in the weld or heat affected zone. The successful application of this indicator results from the large differences in hydrogen solubility and diffusion coefficient between ferrite (martensite) and austenite.

Results: Preliminary results indicate that this analytical approach can qualitatively make predictions of weld hydrogen behaviour.

Plans: Efforts to refine this proposed practice will proceed. Work will expand the range of steel compositions of both plate materials and welding consumables used in this analysis to achieve more quantitative correlations. The thermomechanical simulator (Gleeble) will be used to determine measured austenitic decomposition start temperatures for the various high strength steel plates and weld deposits (welding consumables) of interest. Efforts will be made to promote welding consumable manufacturers to test this proposed practice.

Status: in progress

Completion; 1998, Q3

previously

Task 4

Activity 7



$$M_s \text{ (Andrews)} = 539 - 423 \text{ C} - 30.4 \text{ Mn} - 17.7 \text{ Ni} - 12.1 \text{ Cr} - 7.5 \text{ Mo}$$

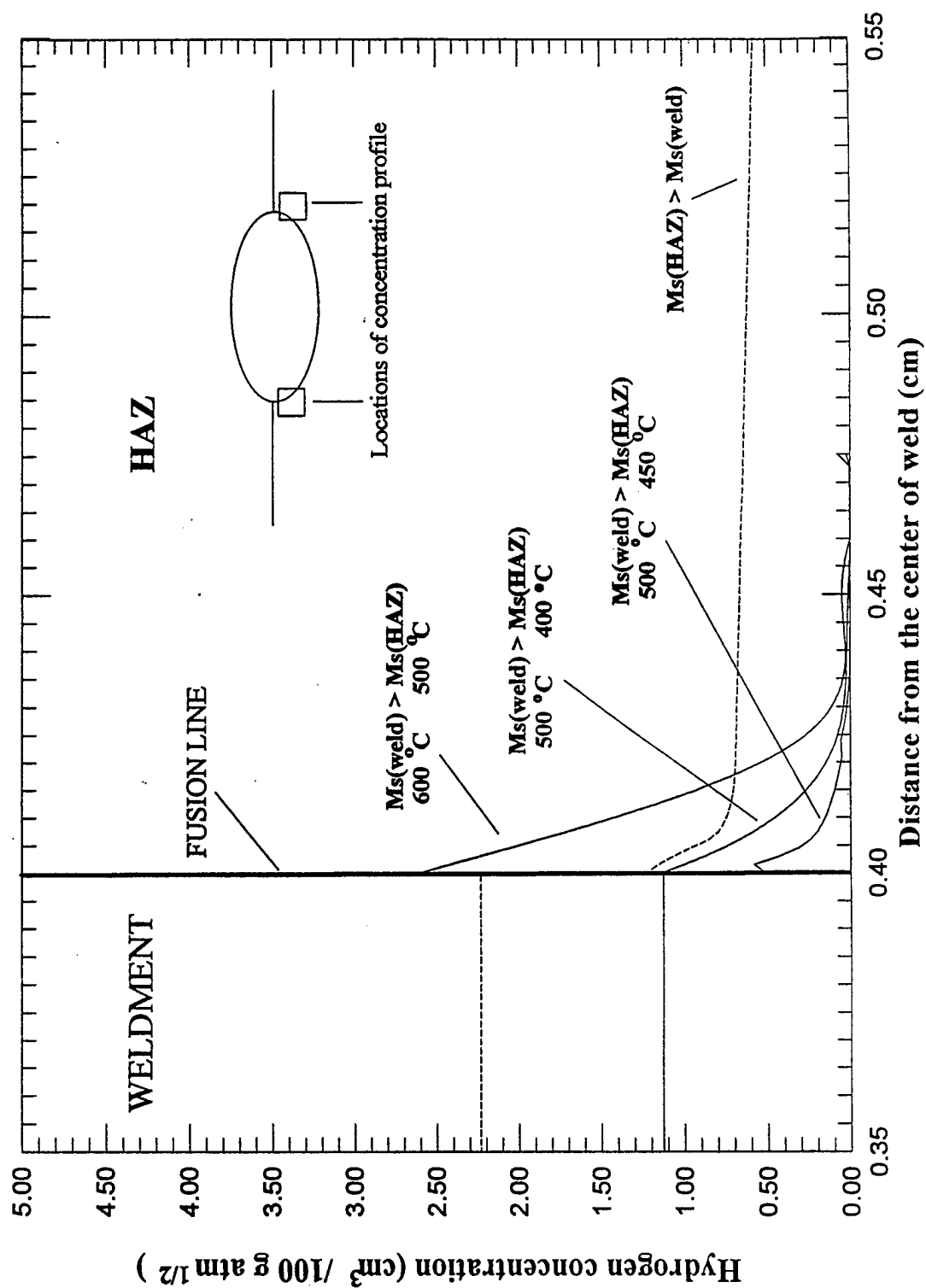
Self et al. (1986)

a) wrought metal

$$M_s = 521 - 350\text{C} - 14.3\text{Cr} - 17.5\text{Ni} - 28.9\text{Mn} - 37.6\text{Si} - 29.5\text{Mo} - 1.19\text{CrNi} + 23.1(\text{Cr} + \text{Mo})\text{C}$$

b) weld metal

$$M_s = 521 - 350\text{C} - 13.6\text{Cr} - 16.6\text{Ni} - 25.1\text{Mn} - 30.1\text{Si} - 40.4\text{Mo} - 40\text{Al} - 1.07\text{CrNi} + 21.9(\text{Cr} + 0.73\text{Mo})\text{C}$$



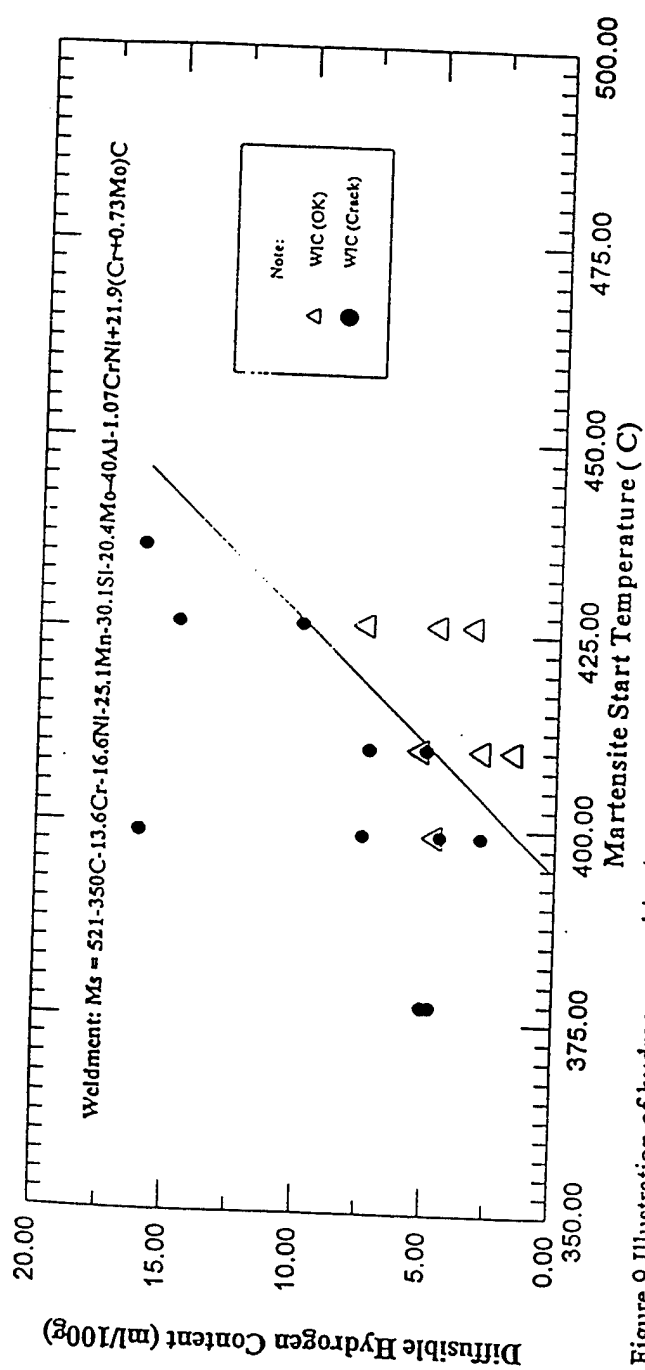


Figure 9 Illustration of hydrogen cracking/uncracking zones by hydrogen content and martensite start temperature.

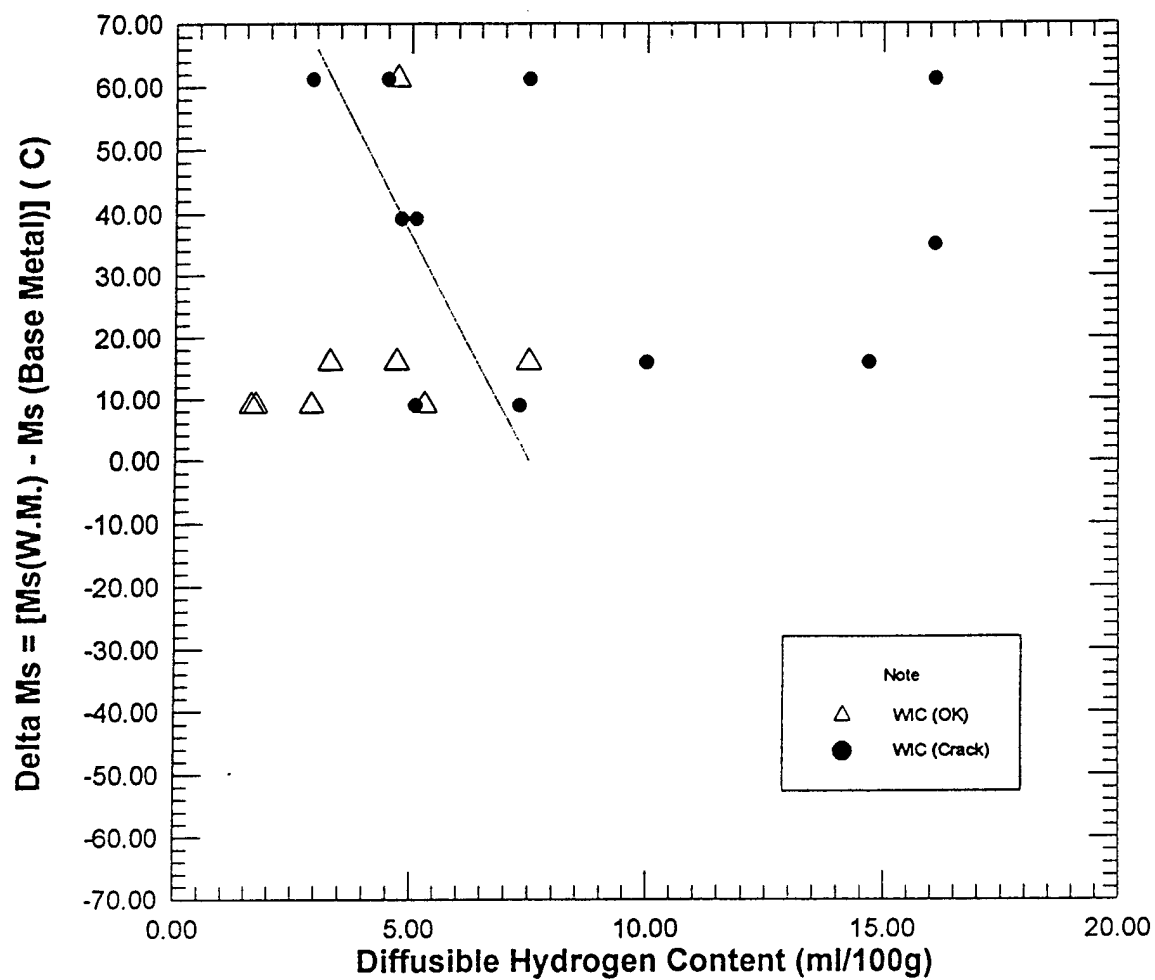
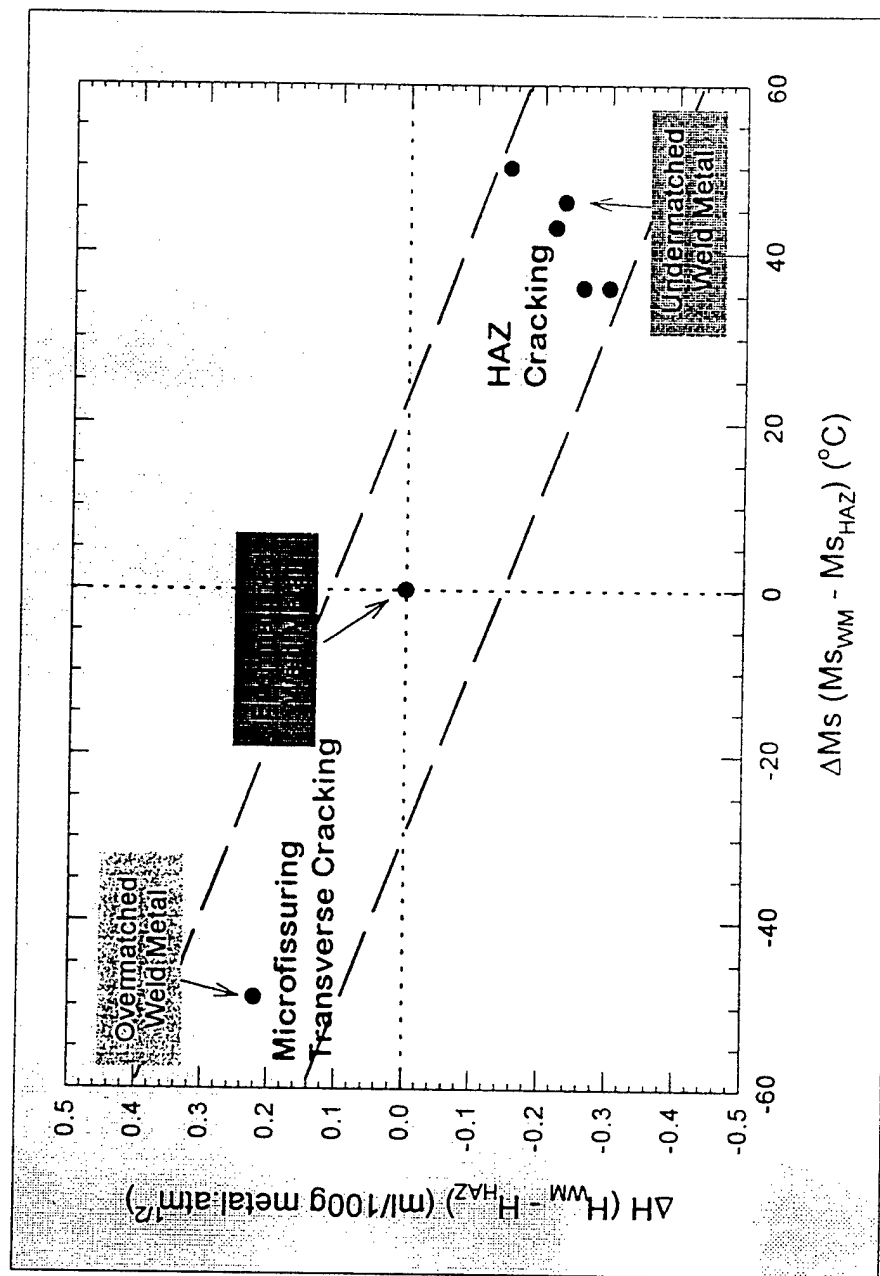


Figure 10 Hydrogen cracking indicated by the martensite start temperature difference between weldment and base metal.

# Weld Undermatching and Overmatching: Non-Uniform Hydrogen Distribution

Weld Cracking Susceptibility -  $\Delta H_{\text{dif}}$



### Task 3: Development of High Strength Steel Filler Metals

#### Activity 7: Multipass Weld Metal Properties

Australia-CISRO

USA-CSM

A cooperative research project between CISRO and CSM is in progress to better understand the influence of alloying additives on the microstructural and mechanical properties of weld metal for flux and metal cored welding. The work is proceeding at each institution and visitations have been made to share data, to discuss alloying and thermal processing models, and to design needed experiments.

Results: Consumables are being made and weld properties are being characterized. The following data is from CISRO efforts.

Plans: work in progress

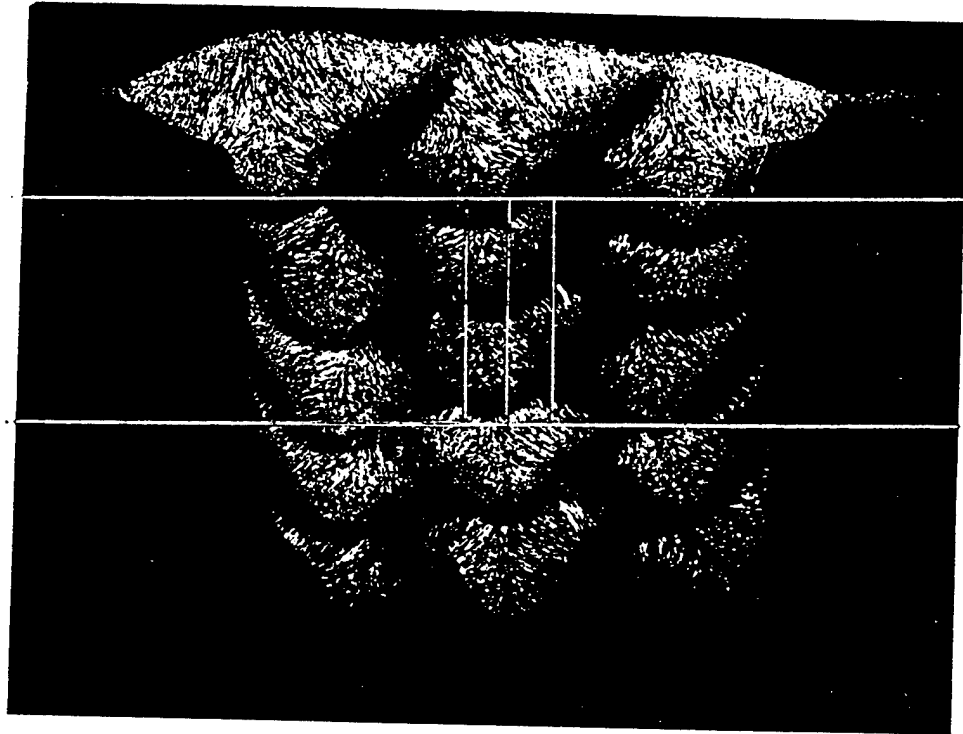
Status: in progress

Conclusion: 1998, Q3

previously

Task 4

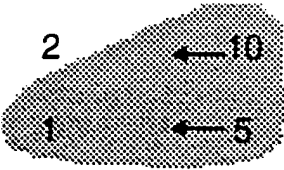
Activity 8



60% As-deposited weld metal  
40% Re-heated weld metal

## WIRE COMPOSITION MATRIX

	Mn	1.1	1.4	1.7
Si	0.4	9	2	10
	0.6	3	1	5
	0.8	7	8	6





### Weld Metal Analysis

Wire	C %	Mn %	Si %	S %	P %	Ni %	Cr %	Mo %	Cu %	V %	Nb %	Ti %	Al %	B %	O %	N %
MC001	.04	1.34	.64	.012	.014	.02	.01	<.01	.01	.0058	.0005	.0054	.0133	<.0005	.053	.0047
MC002	.04	1.45	.39	.012	.014	.03	.01	.01	.01	.0067	.0010	.0050	.0123	<.0005	.055	.0063
MC003	.04	1.00	.57	.007	.016	.02	.01	<.01	.01	.0063	.0001	.0045	.0134	<.0005	.047	.0057
MC005	.04	1.64	.57	.007	.016	.02	.01	.01	.01	.01	<.01	.0060	.0148	<.0005	.048	.0098
MC006	.048	1.66	.84	.014	.017	.019	.013	.008	.008	.008	.005	.0060	.0130	<.0010	.048	.0116
MC007	.05	1.21	.80	.009	.017	.020	.01	.01	.01	.01	<.01	.0059	.0158	<.0005	.044	.0080
MC008	.04	1.27	.67	.007	.016	.02	.01	.01	.01	.01	<.01	.0050	.0140	<.0005	.042	.0106
MC009	.05	.98	.34	.009	.018	.02	.01	<.01	.01	.01	<.01	.0040	.0120	<.0005	.057	.0160
MC010	.05	1.40	.34	.009	.017	.02	.01	.01	.01	.01	<.01	.0051	.0139	<.0005	.043	.0041

### Mechanical Properties

Wire	Reh MPa	Rm MPa	As(El.) %	Z(R.A.) %	Mean Absorbed Energy, J at °C				
					20	0	-20	-40	-60
MC001	507	557	29	70	229	205	159	115	49
MC002	499	541	29	72	207	176	127	40	28
MC003	459	504	30	76	284	203	61	27	11
MC005	549	588	28	71	204	186	153	97	28
MC006	531	601	27	70	112.7	73.7	54	23.4	10
MC007	510	574	18	42	177	159	120	70	24
MC008	521	574	14	--	166	145	60	28	9
MC009	469	523	21	56	220	189	142	48	9
MC010	473	525	26	76	234	238	174	98	42

# CHARPY-V NOTCH IMPACT CURVES

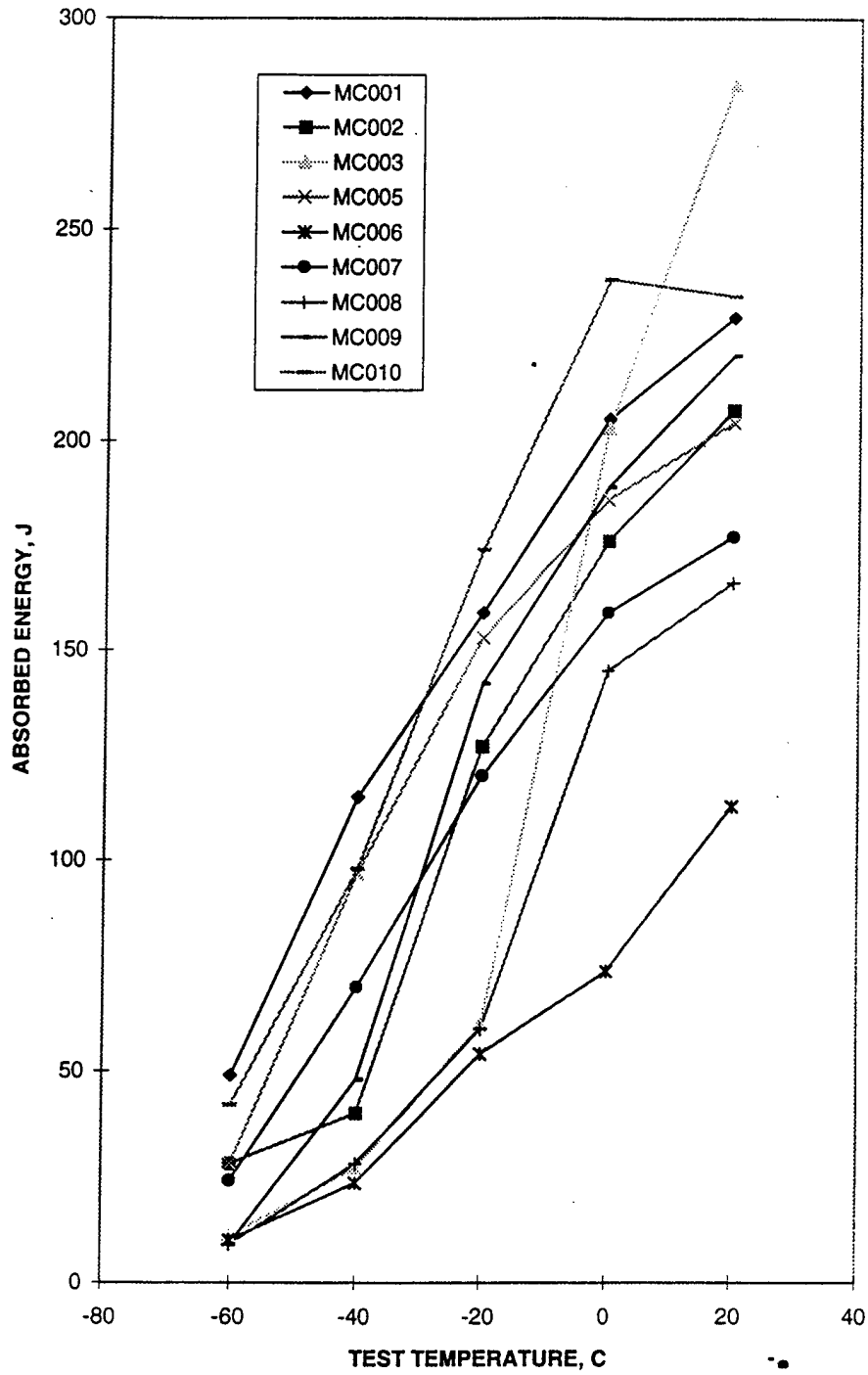
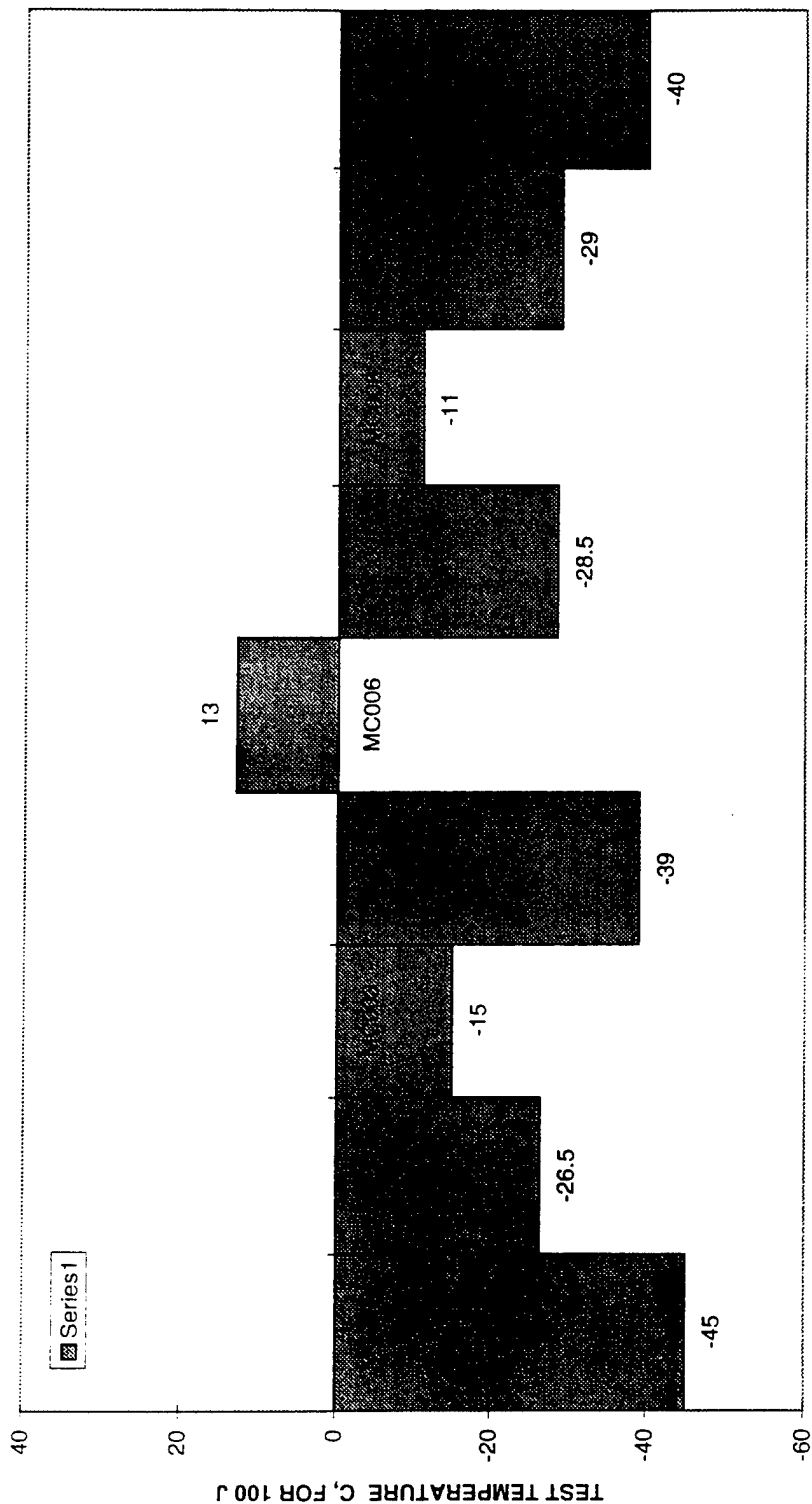


Chart7

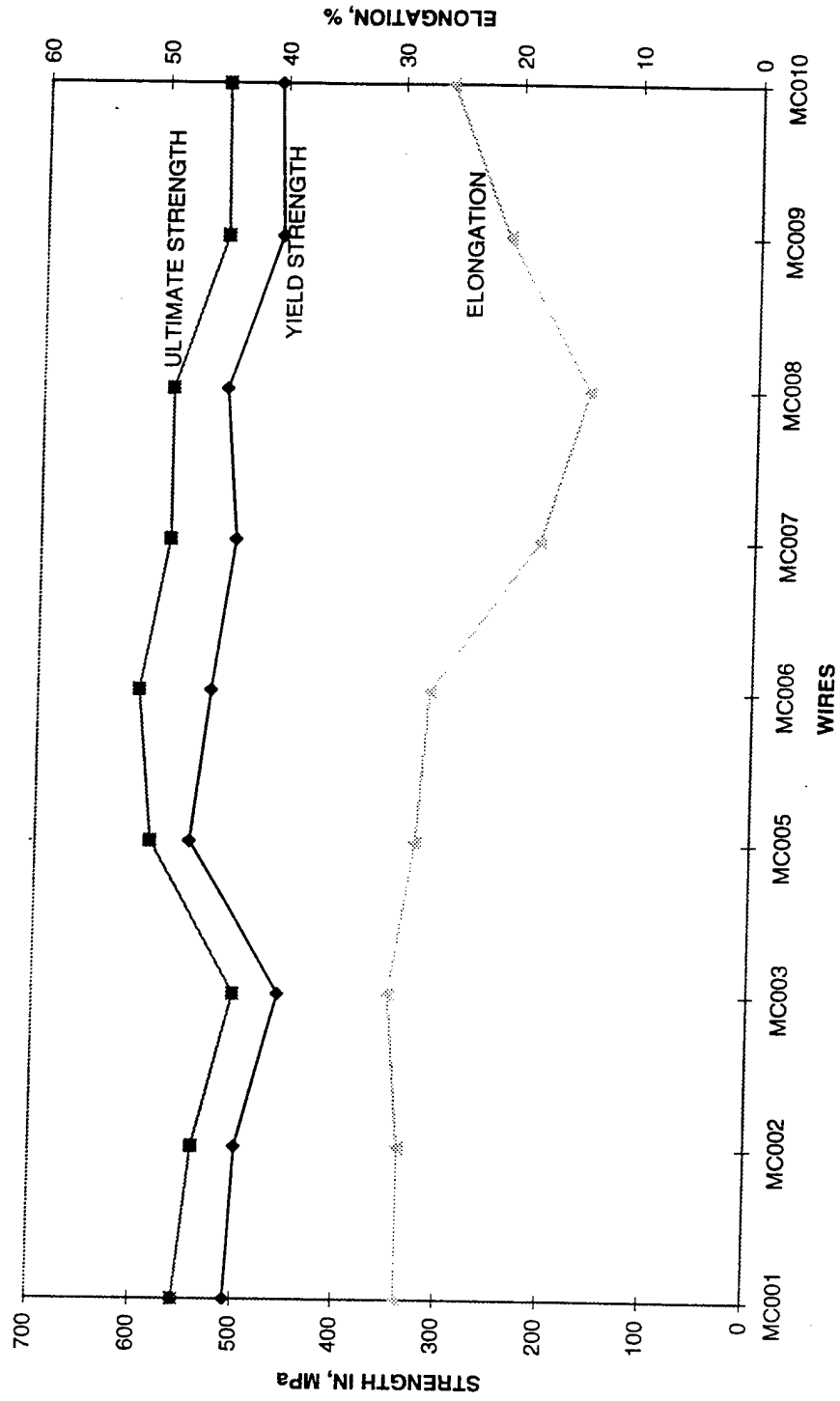
CHARPY-V NOTCH IMPACT ENERGY CORRESPONDING TO 100 J



WIRES

Chart15

MECHANICAL PROPERTIES



### AVERAGE COLUMNAR GRAIN WIDTH

Wire	Grain Size Number	Calculated Dia. Of Average Grain Size mm
MC001	2.715	0.135
MC002	2.37	0.150
MC003	2.5	0.144
MC005	2.57	0.140
MC006	2.78	0.130
MC007	2.68	0.134
MC008	2.67	0.134
MC009	2.57	0.140
MC010	2.58	0.140

### MICROSTRUCTURE OF AS-DEPOSITED WELD METAL

Wire	Primary Ferrite (PF) %	Ferrite with Second Phase (FS) %	Acicular Ferrite (AF) %
MC001	29.9	6.9	62.4
MC002	27.2	11.8	61.0
MC003	33.6	16.5	49.9
MC005	20.7	10.2	69.1
MC006	19.6	9.8	70.6
MC007	37.1	7.9	55.0
MC008	27.3	8.8	63.9
MC009	36.5	12.5	51.0
MC010	28.5	12.7	58.8

# MICROSTRUCTURE OF AS-DEPOSITED WELD METAL (0.4 Si)

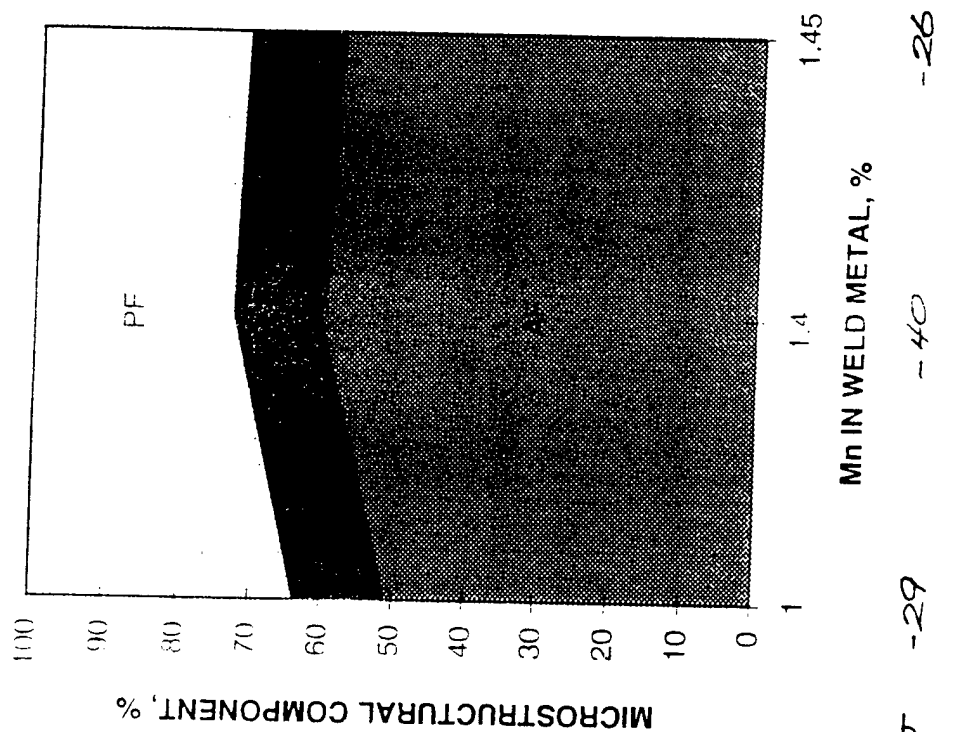
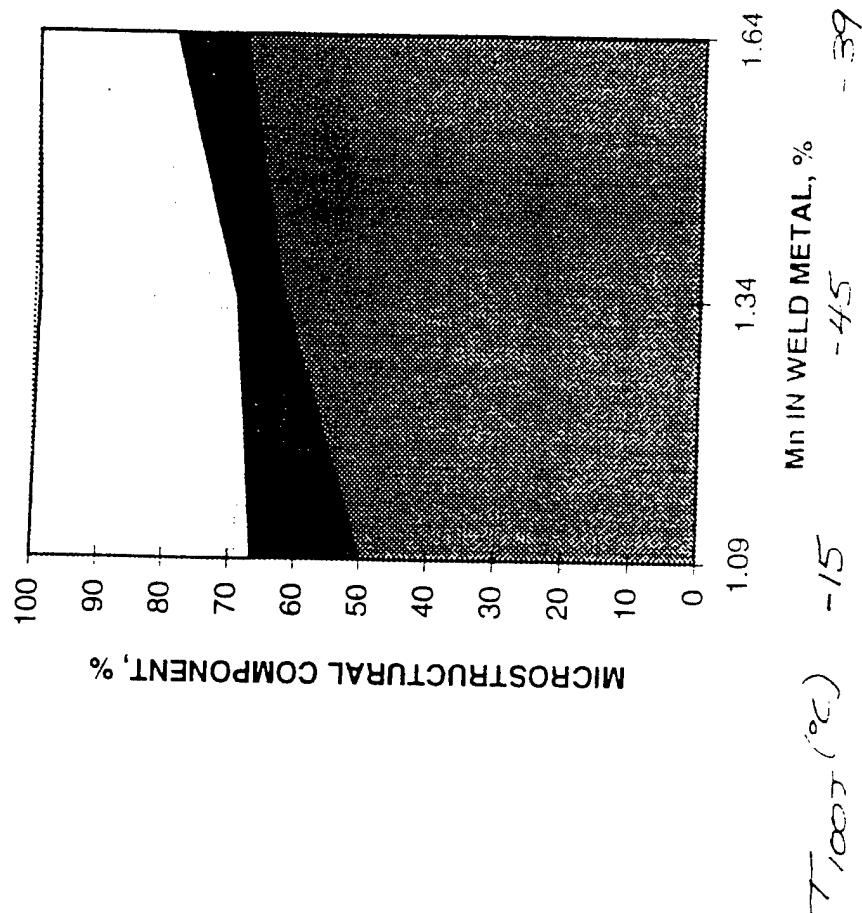
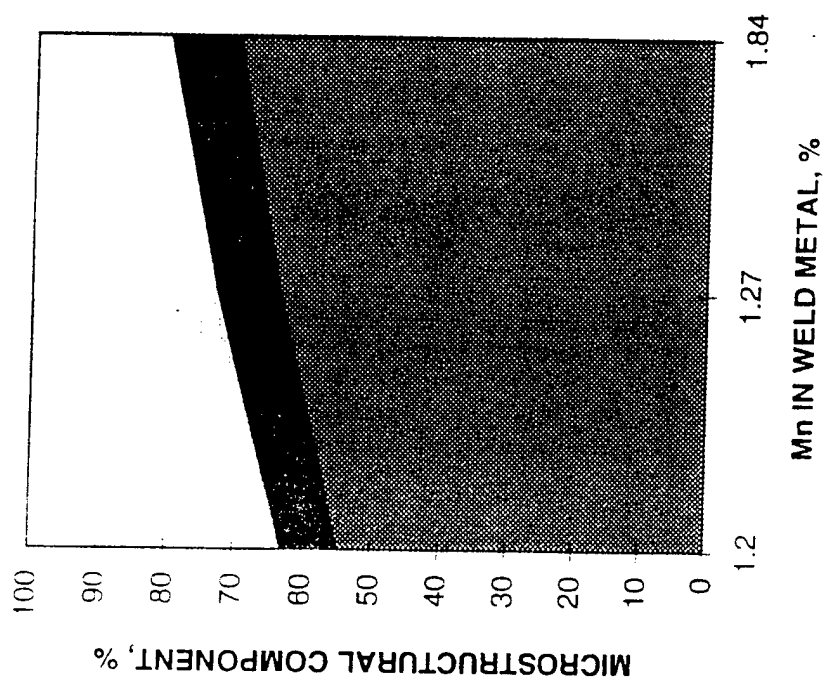


Chart13

# MICROSTRUCTURE OF AS-DEPOSITED WELD METAL (0.6Si)



# MICROSTRUCTURE OF AS-DEPOSITED WELD METAL (0.8 Si)



$T_{1000}$   
 (°C)

-28	-11	+13
-----	-----	-----



### Task 3: Development of High Strength Steel Filler Metals

#### Activity 8: Use of Weld Metal Traps for Hydrogen Management

##### USA-CSM

The use of weld metal hydrogen traps to reduce the available diffusible hydrogen content is being investigated. From literature reported and theoretically calculated binding energy values calculations have been made to assist in the selection of the most promising ferroadditions to be added to welding consumables.

Results: Selected ferroadditions of various transition metals and rare earths were made by CSM. Lincoln Electric Company has made metal filled cored wires with these additions at various content levels. A reproducible method to introduce a specific hydrogen content into the weld metal was developed to allow for the evaluation of this concept of hydrogen management. An analytical arrangement and procedures to measure the hydrogen evolution rate as a function of weldment have been set up. Efforts have begun to measure the effectiveness of the Lincoln Electric produced experimental (with trapping additions) consumables. Preliminary results have shown drops in the diffusible hydrogen content due to trapping.

Plans: The investigation will continue with a thorough hydrogen analysis of the Lincoln Electric prepared consumables. The weld metal microstructure will be characterized to determine the type, size, size distribution and amount of weld metal traps. It is anticipated that after this first phase is completed another set of experimental consumables will be made using the addition which demonstrated the most promise. The second set of consumables should allow for optimization of content of the consumable trapping addition, weld metal oxygen content, and alloying contents for a specific welding heat input range.

Status: in progress

Completion: 1998, Q3

previously

Task 67  
Activity 8

# Hydrogen Trapping

## Assessment of Trapping Parameters

### Hydrogen - trap site binding (interaction) energy

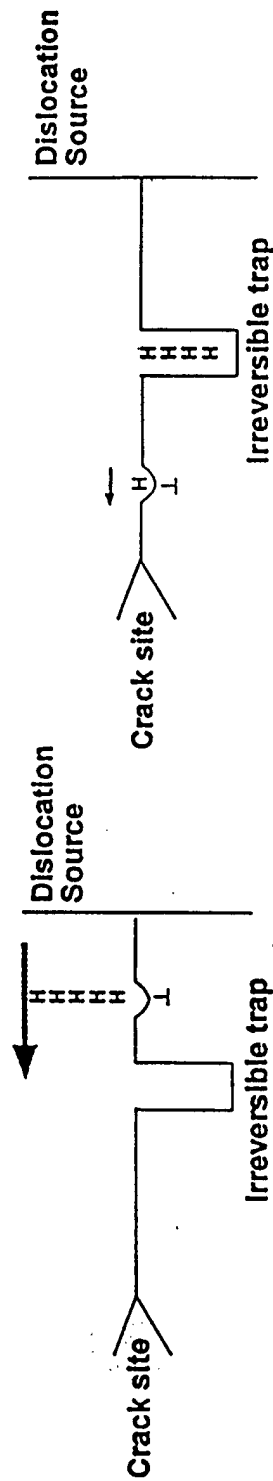
Table 1. Hydrogen trapping in Iron. Reference state :  $\bar{H}$  in perfect lattice

Trap Site	Binding Energy (kJ/mol)	Matrix	Assessment Method	Ref.
H-dislocation elastic stress field	0 - 20.2	Iron	calculated	19
H-dislocation core (screw)	20 - 30	Iron	calculated	11
H-dislocation	26	Iron	thermal analysis	20
H-dislocation core (mixed)	59	Iron	permeation	21
H-grain boundary	18 - 20	C-Mn Steel	thermal analysis	20
H-grain boundary	60	Iron	thermal analysis	22
H-grain boundary	59	Iron	permeation	21,23
H-Free surface	70	Iron	permeation	24
H-Free surface	95	Iron	permeation	25
$\beta$ -NiAl	27	Steel *	permeation	26
H-PdAl interface	34	Steel *	permeation	25
H-Fe-oxide interface	47	C-Mn Steel	thermal analysis	27
H-AlN interface	65	Iron	permeation	28
H-MnS interface	72	C-Mn Steel	thermal analysis	29
H-Al <sub>2</sub> O <sub>3</sub> interface	79	C-Mn Steel	thermal analysis	30
H-Fe <sub>3</sub> C interface	84	C-Mn Steel	permeation	23,31
H-TiC interface	87	Iron	thermal analysis	32
H-TiC interface	95	C-Mn Steel	permeation	33
H-Nd	129	Iron	calculated	34

\* Matrix element is precipitation hardened martensitic stainless steel.

## Hydrogen Trapping

The role irreversible trap sites in preventing hydrogen induced cracking



- Before a dislocation pass through an irreversible trap site
  - High dislocation velocity
  - High potential for hydrogen accumulation at the crack tip
- After a dislocation pass through an irreversible trap site
  - Low dislocation velocity
  - Low potential for hydrogen accumulation at the crack tip

## Ab-initio predictions of Hydrogen trap depths

1) For the traps modeled (carbides of Ti, Nb, V and Mo and oxides of Ce and Y) ab-initio calculations have shown that hydrogen trapping occurs at the bulk-trap interface.

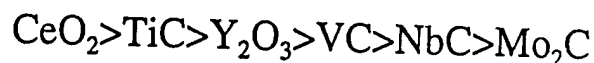
2) A correlation between the type of bonding at the trap-bulk interface and the hydrogen to trap binding energy has been seen.

Effective traps are those where the Fermi energy is dominated by trap electronic states with little or no contribution from the bulk.

Of these, the most effective traps are those where the Fermi energy orbitals display  $\sigma$  or  $\pi$  type bonding across the trap-bulk interface. Less effective are those that where the Fermi energy orbitals display  $\delta$  type bonding across the interface.

3) These facts are interpreted as indicating that H s-orbitals overlap strongly where there is available trap electron density across the interface giving rise to strong trap-H bonds.

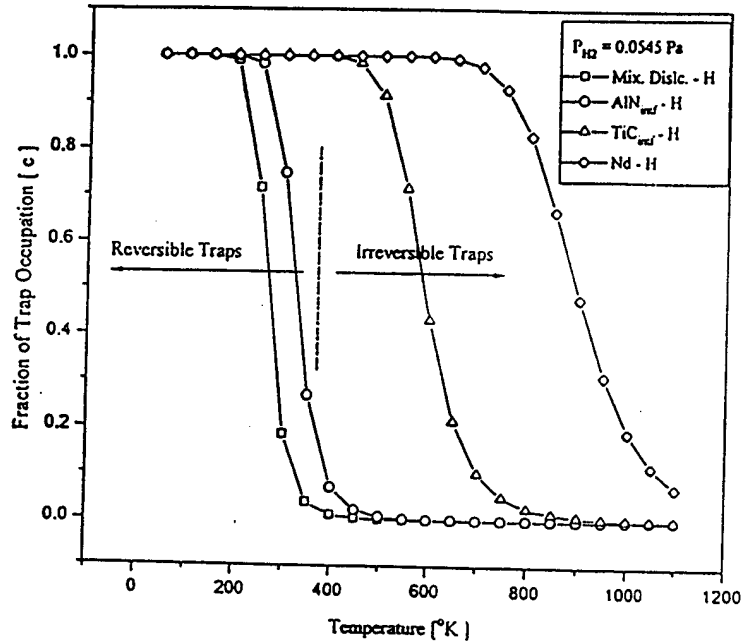
4) From this correlation the effectiveness of the modeled materials as hydrogen traps decreases through the series



## Hydrogen Trapping

### Trap occupation by hydrogen as predicted by Fermi-Dirac distribution

Fraction of trap occupation as a function of temperature for various type of traps at hydrogen partial pressure  $P_{H_2} = 0.0545 \text{ Pa}$



1. Open system:  $\frac{1}{2}H_2 = \underline{H}$ , at  $H_2$  pressure =  $P$

$$c_H = 0.00185\sqrt{P} \exp\left(\frac{28600}{RT}\right), \quad [P : \text{atm}]$$

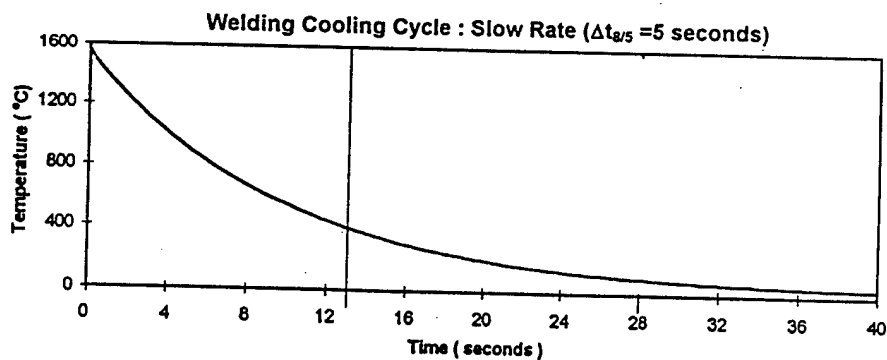
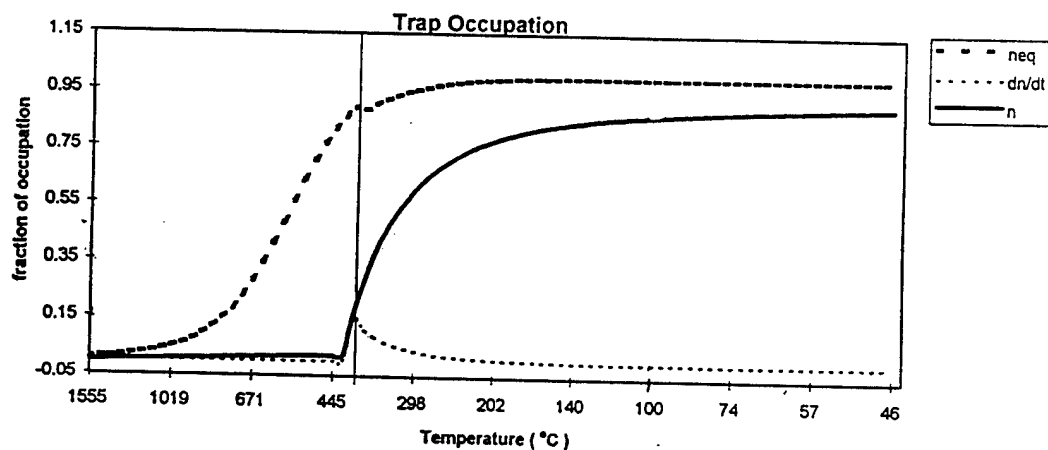
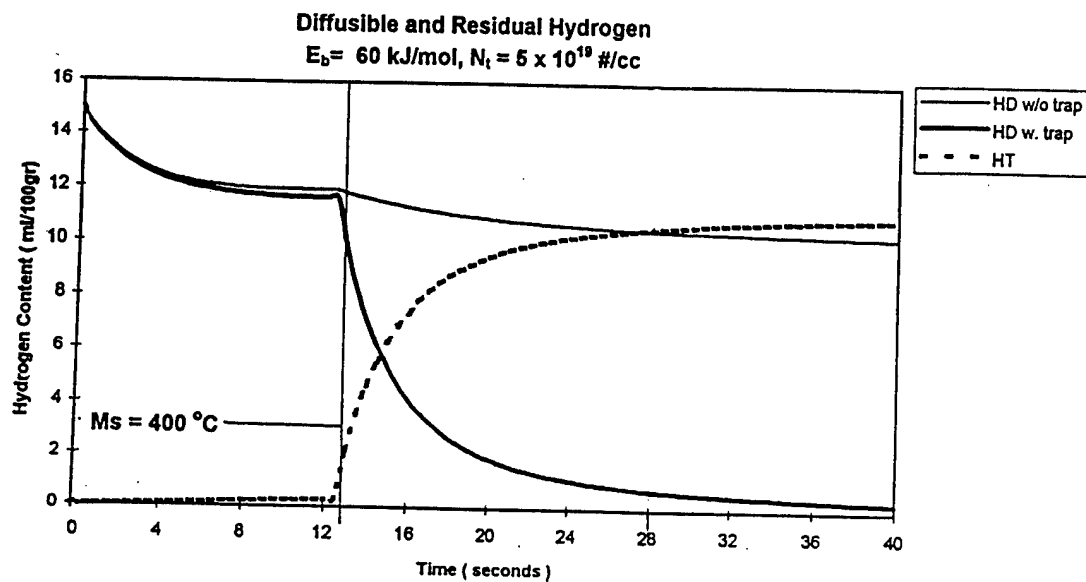
$$[T : ^\circ K]$$

2. Trapping:  $\underline{H} + X = H_x$

$$\frac{c}{1-c} = \frac{c_H}{1-c_H} \exp\left(\frac{E_b}{RT}\right) \equiv c_H \exp\left(\frac{E_b}{RT}\right), \quad [E_b : \text{kJ/mol}]$$

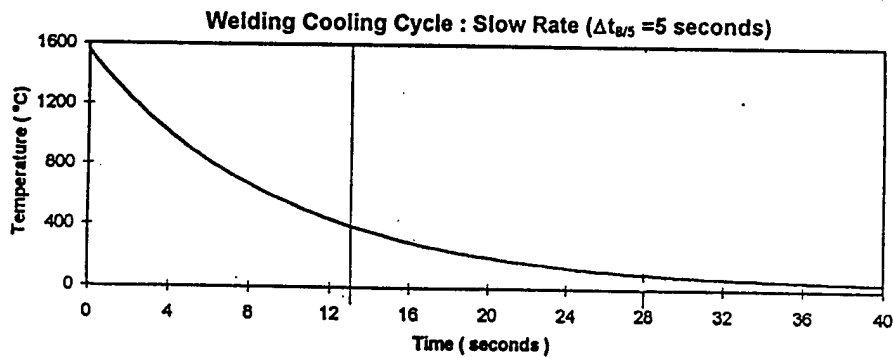
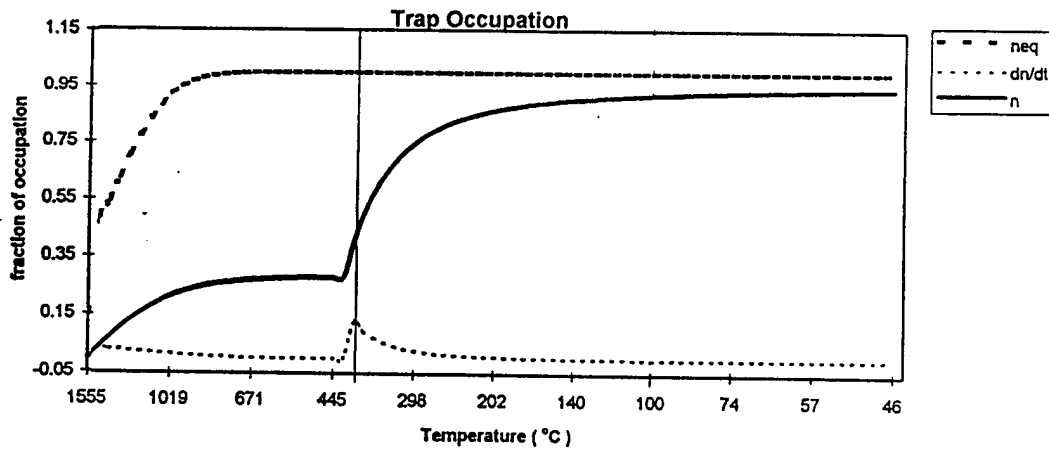
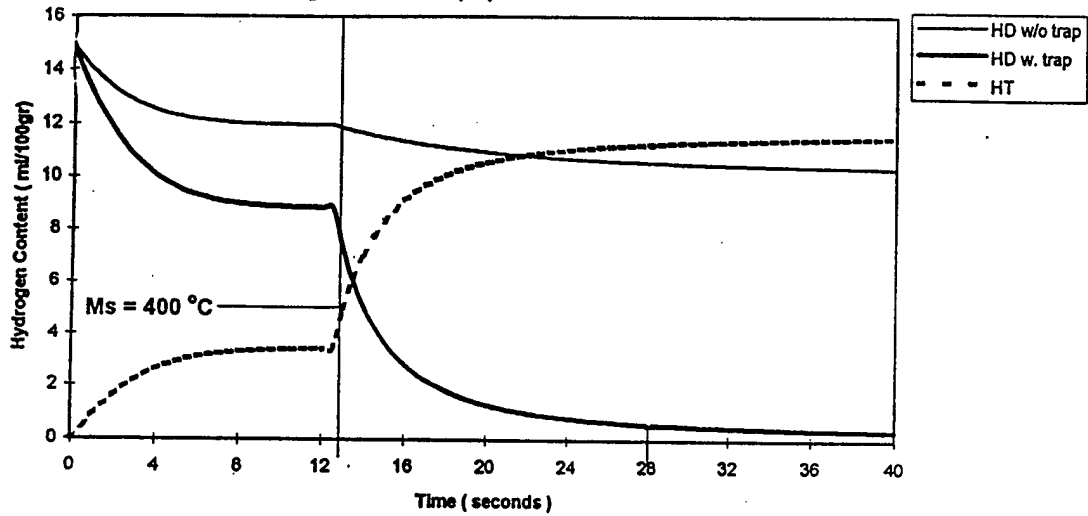
where  $E_b$  = Trap - H binding energy

$$1+2. \quad \frac{c}{1-c} = 0.00185\sqrt{P} \exp\left(\frac{E_b - 28600}{RT}\right)$$



### Diffusible and Residual Hydrogen

$E_b = 120 \text{ kJ/mol}$ ,  $N_t = 5 \times 10^{19} \text{ \#/cc}$



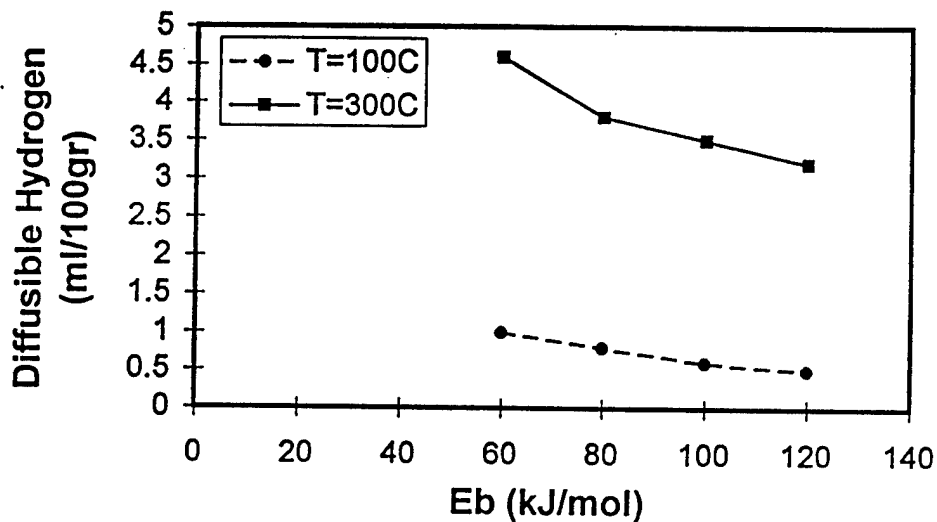
## Effect of Trap Binding Energy

Initial Diffusible Hydrogen Content = 15 ml/100 gr

$M_s = 400^\circ\text{C}$

$\Delta t_{8/5} = 5$  seconds

$N_t = 5 \times 10^{19} \text{ \#/cc}$



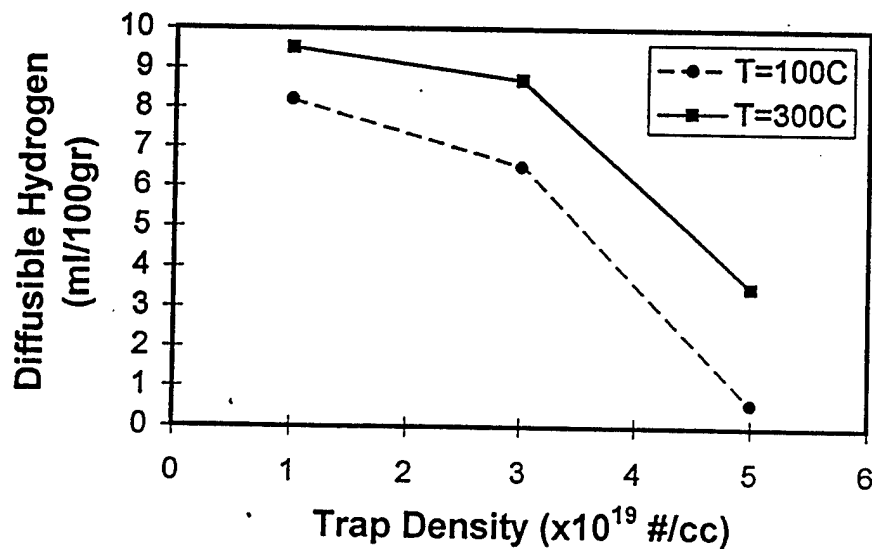
## Effect of Trap Density

Initial Diffusible Hydrogen = 15 ml/100 gr

$E_b = 100 \text{ kJ/mol}$

$\Delta t_{8/5} = 5$  seconds

$M_s = 400^\circ\text{C}$





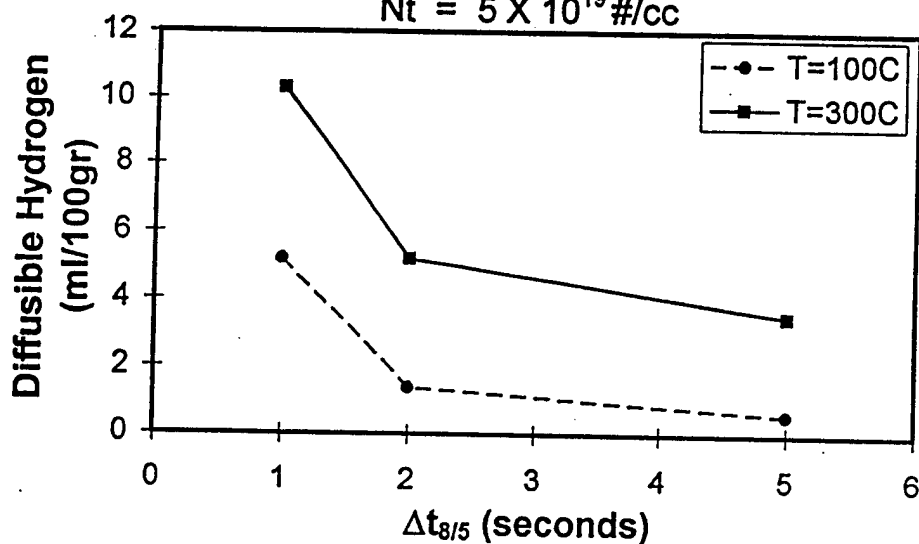
## Effect of Cooling Rate

Initial Diffusible Hydrogen Content = 15 ml/100 gr

$M_s = 400^\circ\text{C}$

$E_b = 100 \text{ kJ/mol}$

$N_t = 5 \times 10^{19} \text{ \#/cc}$



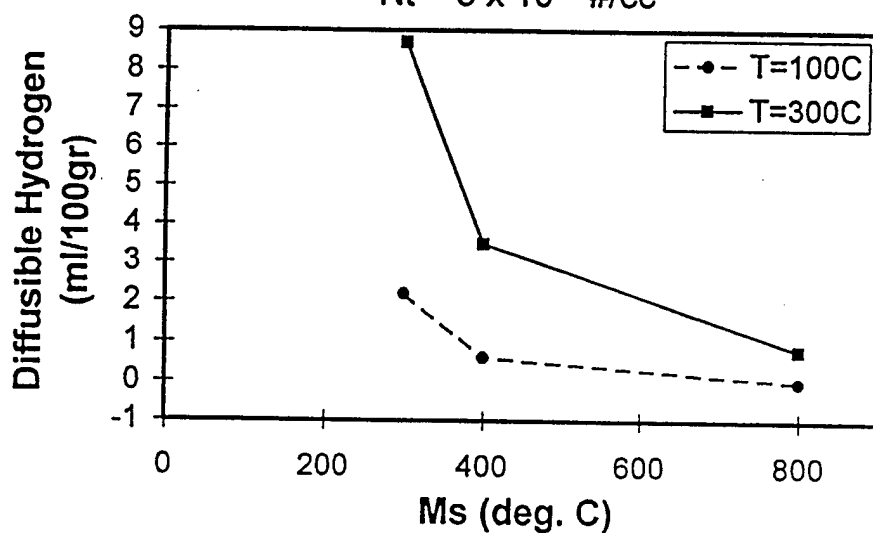
## Effect of $M_s$ Temperature

Initial Diffusible Hydrogen = 15 ml/100 gr

$E_b = 100 \text{ kJ/mol}$

$\Delta t_{8/5} = 5 \text{ seconds}$

$N_t = 5 \times 10^{19} \text{ \#/cc}$



## EXPERIMENTAL

- Materials
  - HSLA 100 Steel Base Plate
  - Metal-Cored Electrodes (Lincoln Electric, Co.)
  - Transition Metal Elements: Ti, V
  - Rare Earth Elements: Y, Ce, Nd, Er
- Process
  - GMAW
  - Hydrogen Introduced Through Shielding Gas

# Hydrogen Gettering (ONR) Direct Study

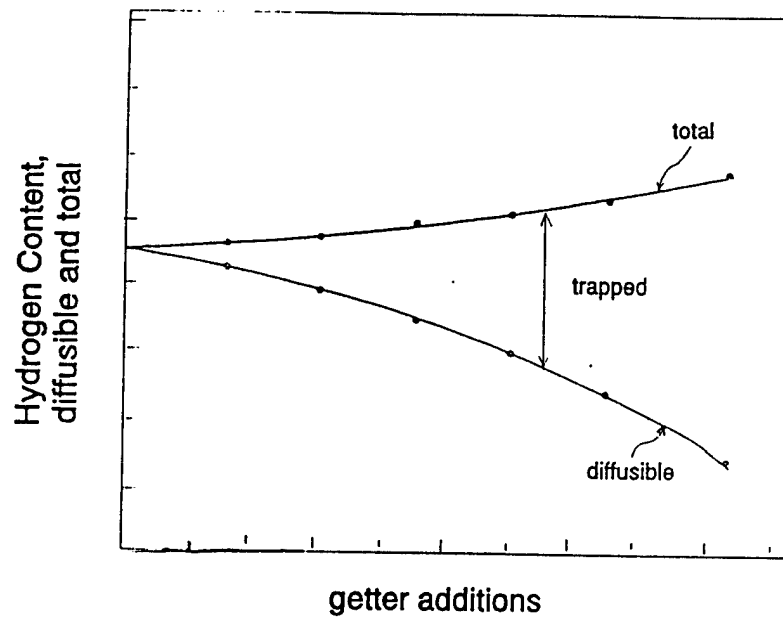
HSLA 100 Base Metal and Corresponding HSLA 100 Electrode

Table II Metal Cored Electrode Designations for Rare Earth and  
Transition Metal Gettering Study

Electrode Designation	Rare Earth Elements	Weld Deposit Composition (wt. %)
GE-Y1	Yttrium	0.08%Y (500ppm), (other)*
GE-Y2	Yttrium	0.16%Y (1000ppm), (other)*
GE-Y3	Yttrium	0.32%Y (2000ppm), (other)*
GE-Ce1	Cerium	0.13%Ce (500ppm), (other)*
GE-Ce2	Cerium	0.25%Ce (1000ppm), (other)*
GE-Ce3	Cerium	0.50%Ce (2000ppm), (other)*
GE-Nd1	Neodymium	0.13%Nd (500ppm), (other)*
GE-Nd2	Neodymium	0.26%Nd (1000ppm), (other)*
GE-Nd3	Neodymium	0.52%Nd (2000ppm), (other)*
GE-Er1	Erbium	0.15%Er (500ppm), (other)*
GE-Er2	Erbium	0.30%Er (1000ppm), (other)*
GE-Er3	Erbium	0.60%Er (2000ppm), (other)*
Electrode Designation	Transition Metal Elements	Weld Deposit Composition (ppm)
GE-Ti1	Titanium	200ppm Ti, (other)*
GE-Ti2	Titanium	300ppm Ti, (other)*
GE-Ti3	Titanium	400ppm Ti, (other)*
GE-V1	Vanadium	200ppm V, (other)*
GE-V2	Vanadium	300ppm V, (other)*
GE-V3	Vanadium	400ppm V, (other)*

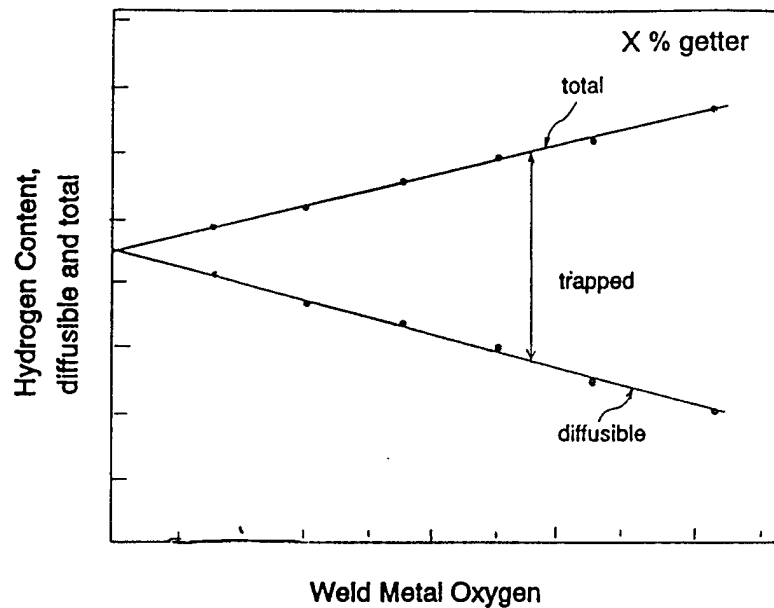
NOTE: (other)\* - remaining composition for HSLA 100 Electrode

## HYDROGEN CONTENT



- Total Hydrogen Content
- Diffusible Hydrogen Content

## OXYGEN EFFECT



- Vary weld metal oxygen through shielding gas to simulate variation in the range of welding conditions.
- The oxygen tests are to evaluate the stability and effectiveness of the best predominating getter addition and content determined in the first experiment.

## CHARACTERIZATION

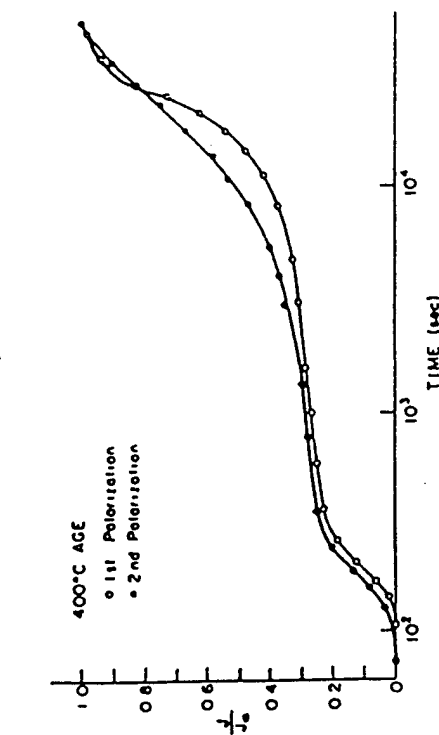
- SEM
  - \* Microstructure
- TEM
  - \* Inclusions
    - Count or Density
    - Size Distribution
    - Chemical Analysis
  - \* Dislocation Substructure
- Weld Composition

# Hydrogen Trapping

## Assessment of Trapping Parameter Permeation Technique

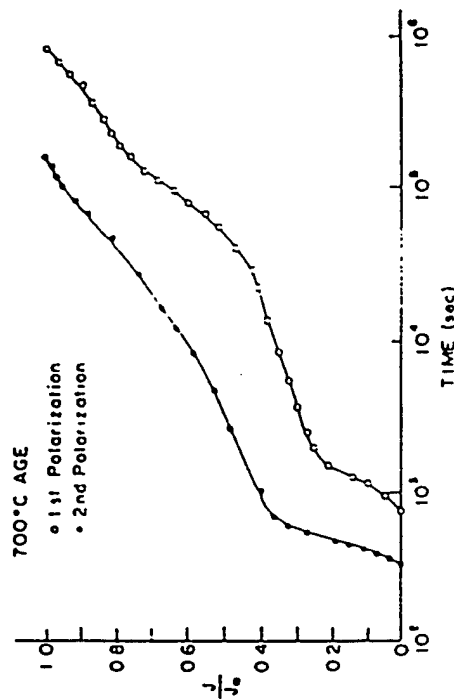
### Typical hydrogen permeation flux of samples containing hydrogen traps

M.F Stevens and I.M. Bernstein, 1989



(a)

- Sample containing reversible traps only.
- The presence of the traps is indicated by the plateau in the hydrogen flux.
- Evidently show that reversible traps are not saturable and thus show that the apparent diffusivity of hydrogen in the alloy is due to reversible traps



(b)

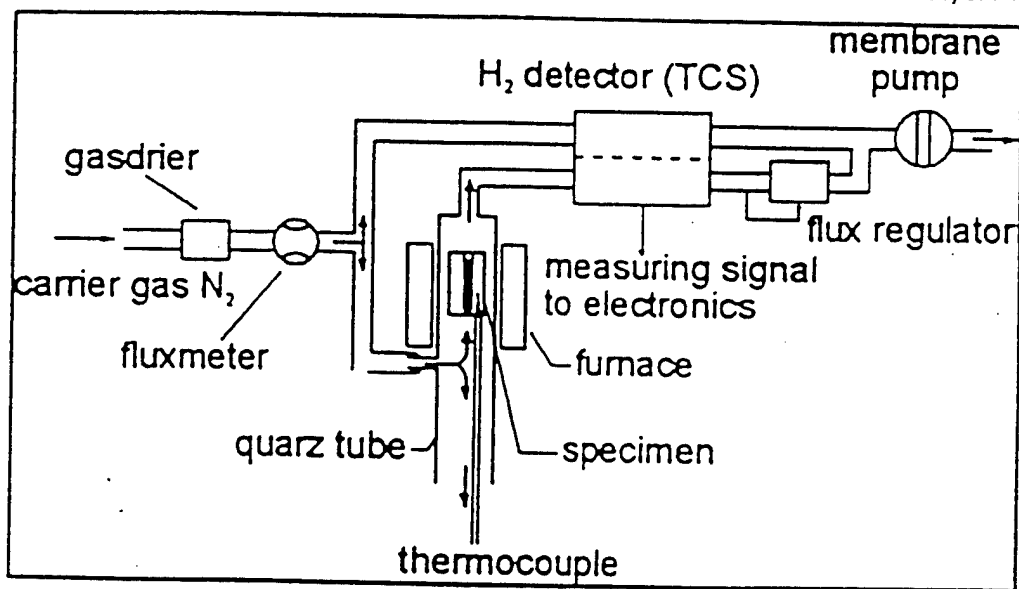
- Sample containing both the reversible and the irreversible traps.
- The area difference between the first polarization and the second one depends on the number of the irreversible traps.
- Irreversible traps are saturable and do not contribute to the apparent hydrogen diffusivity

# Hydrogen Trapping

## Assessment of Trapping Parameters

### Thermal Analysis

S. Trube, 1994



Thermal analysis : typical equipment set up

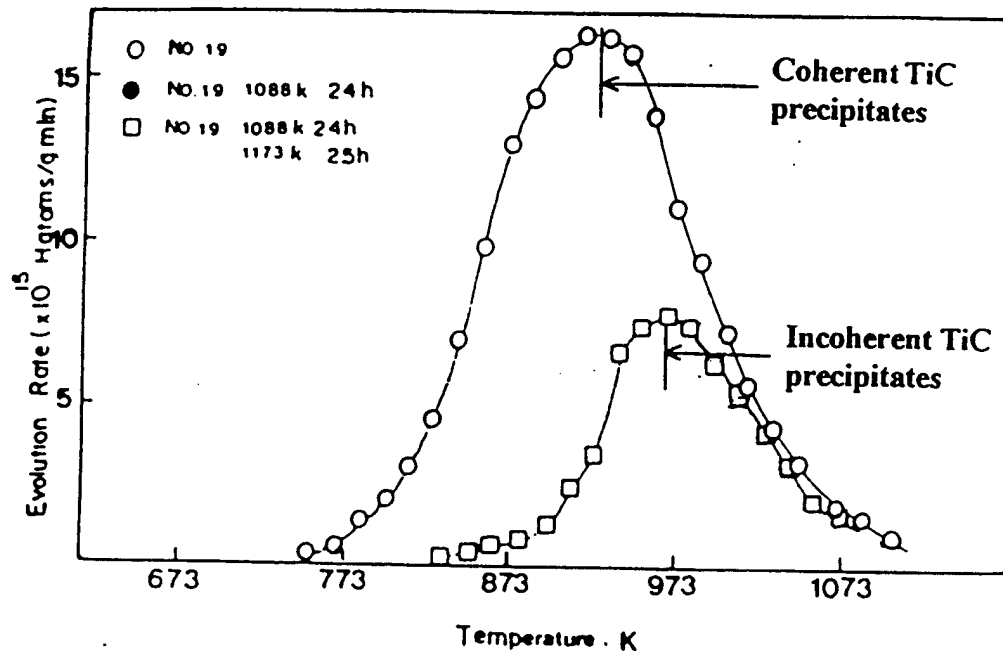


# Hydrogen Trapping

## Assessment of Trapping Parameters

### Thermal Analysis

S.M. Lee and J.Y. Lee, 1987



**Thermal analysis result : effect of precipitates interface coherency on the depth of its trapping capacity**

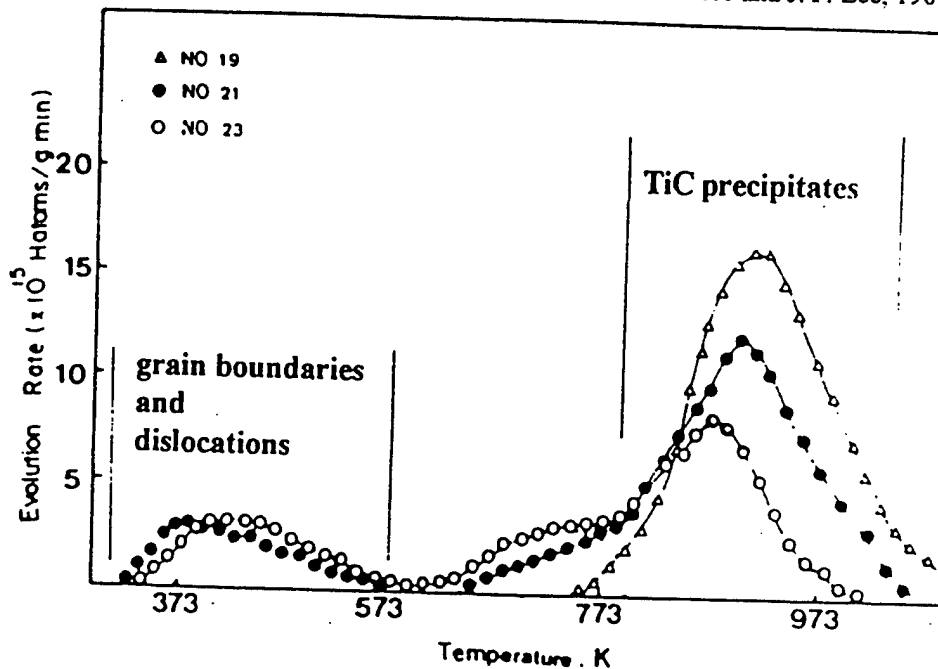
- The effect of the degree of coherency of TiC precipitate interface on trapping binding energy.
  - Sample containing coherent TiC precipitates with lowest binding energy but largest number of trap sites.
  - Sample containing incoherent TiC precipitates with the highest binding energy but fewest number of trap sites.

# Hydrogen Trapping

## Assessment of Trapping Parameters

### Thermal Analysis

S.M. Lee and J.Y. Lee, 1987



### Typical thermal analysis result : hydrogen evolution from different types of traps

- Hydrogen gas evolves from a hydrogen charged sample, which is heated with a constant heating rate.
- The peak evolution rate of hydrogen occurs at a temperature closely related to the trap binding energy.
- The higher the binding energy, the higher the peak evolution temperature.
- From the above figure, the lower peak evolution temperature corresponds to hydrogen released from grain boundary whose binding energy is 20–60 kJ/mol. The higher peak evolution temperature corresponds to hydrogen released from TiC precipitates, which are irreversible traps with binding energy of 90 kJ/mol.

### Task 3: Development of High Strength Steel Filler Metals

#### Activity 9: Analytical Methods to Evaluate Weld Hydrogen Distribution

USA-CSM

USA-SUNY-Albany

The hydrogen distribution in a weld becomes significantly more important as the acceptable diffusible hydrogen contents decrease. With the ever increasing use of steels of higher strength analytical techniques need to be developed to measure hydrogen distribution across the weld. These localized hydrogen contents are most likely the cause in the spread of the correlation between the measured diffusible hydrogen contents and cracking tendencies. Two methods that have been able to measure hydrogen distributions are laser induced breakdown spectroscopy (LIBS) and MeV ion Beam Analysis.

Results: Preliminary results for both techniques have successfully measured hydrogen distributions.

Plans: Efforts will be made to develop an analytical practice to supplement the information presently reported by the diffusible hydrogen measurements.

Status: in progress

Completion: 1999, Q3

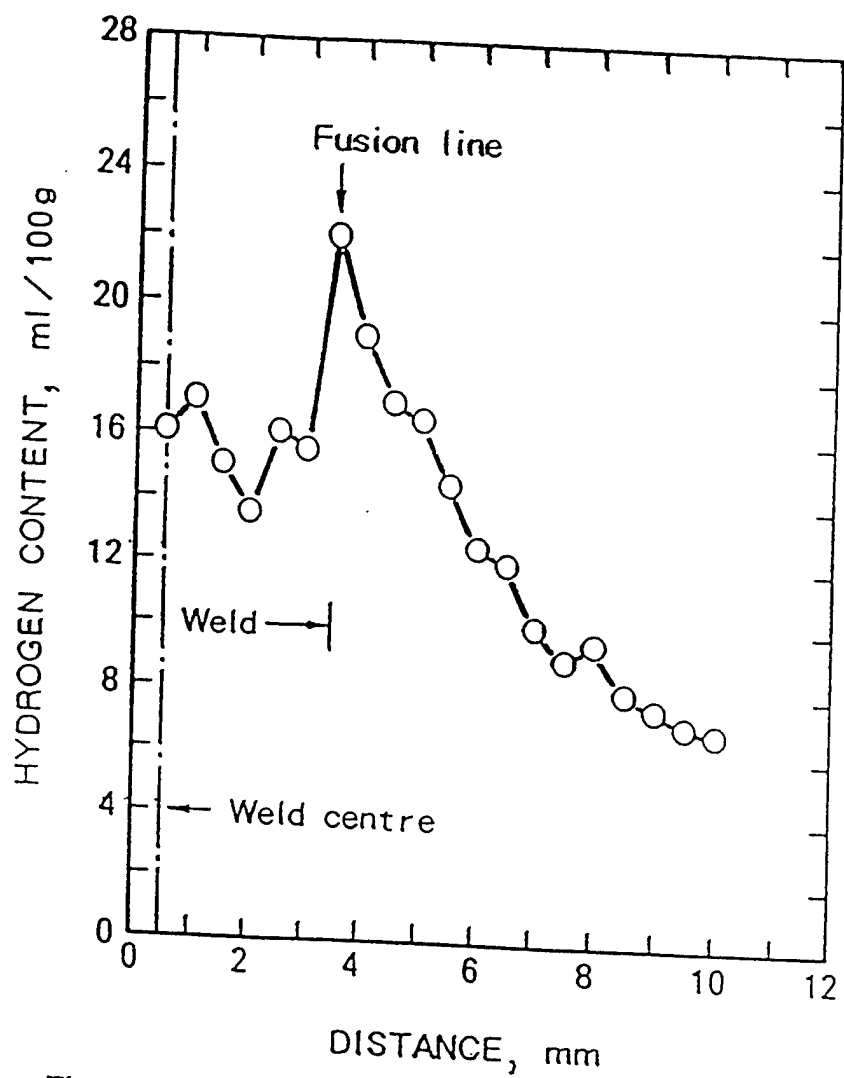
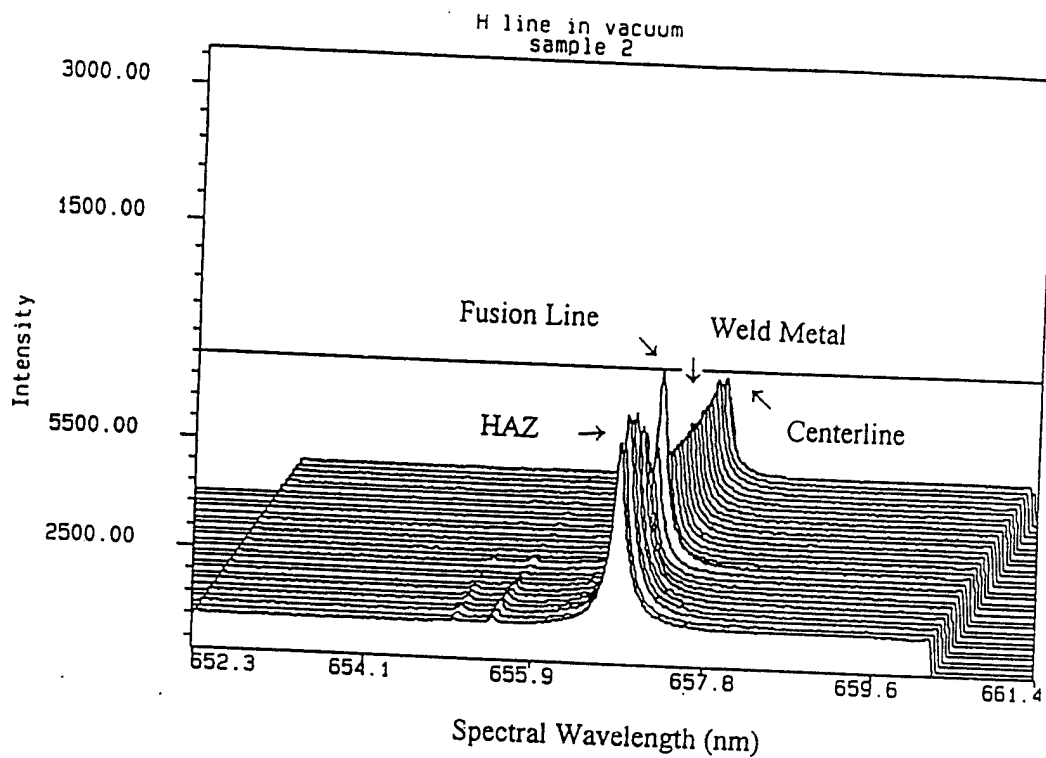


Figure 4 Hydrogen distribution across the weld fusion line (17).



Non-uniform distribution of hydrogen across the center line of a weldment. Intensities of hydrogen spectral emission are proportional to the hydrogen concentration

## **SECTION VII**

**Manpower (man years) in 1996**

Manpower                      man years

USA-NSWCCD	4.5
USA ARMY-Benet	1.2
USA ARMY-ARL	0.3
USA-CSM	2.0
AUST. DSTO	1.2
AUST. CISRO	1.0
AUST. ASC	0.1
Canadian	0.4
U.K.	0.0
N.Z.	0.0
Total	10.7

## **SECTION VIII**

### **List of Participants**



NAME	AFFILIATION
Len Davidson	DSTO
Brian Dixon	DSTO
Bob Phillips	DSTO
Stan Lynch	DSTO
John Ritter	DSTO
Steve Burke	DSTO
Ahmit Majumdar	DSTO
Alan Cuthbert	WTIA
Dave Olson	Colorado School of Mines
Mark Eberhart	Colorado School of Mines
Richard Wong	Naval Surface Warfare Center or NSWC
Joe Blackburn	Naval Surface Warfare Center or NSWC
Robert Weber	US Army CERL
Damian Kotecki	Lincoln Electric Co.
Bill Lanford	State Univ. of New York
Gregory Vigilante	US Army ARDEC
Igor Pokhodnya	E.O. Paton Welding Inst.
Andrew Crowson	US Army Research Office
Edward Chen	US Army Research Office
Liang Chen	University of Wollongong
Nazmul Alam	University of Wollongong
Calvin Hyatt	Defence Research Establishment
Ralph Adler	US Army Research Laboratory